CCUS Technologies in Greece

Prospects for implementation

IENE Study, October 2023

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INSTITUTE OF ENERGY
FOR SOUTH-EAST EUROPE

An IENE Study (M64)

Prospects for the Implementation of CCUS Technologies in Greece -Extended Summary

October 2023

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An IENE Study Project (M64)

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This IENE Study has been supported by the following companies which have acted as Partners to IENE on this project:

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- DESFA
- Franco Compania Naviera S.A.
- HELLENiQ ENERGY
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Introduction

In July 2020, the Institute completed a major study on "The current situation and prospects for areas in Energy Transition in Greece". The study was undertaken by IENE upon the invitation of the Ministry of Environment and Energy (YPEN) in order to assess the energy and economic potential of the various regions in Greece which were earmarked for fast Energy Transition. An important part of the study examined the situation in West Macedonia and Megalopolis in Peloponnese, in relation to lignite and its use for power generation. Greece at the time had some 4.0GW of installed capacity of lignite power plants, some of which are already retired or mothballed, while the rest will cease operating by the end of 2028, in compliance to the Greek government's decarbonisation plan. A brand-new unit, the 610MW Ptolemais V, came on stream at the beginning of 2023 and has to be retired by the end of 2028, according to the government's original decarbonisation plan.

In carrying out the aforementioned study, the need was identified for maintaining at least some of the lignite-fired power generating capacity beyond 2028 for energy security reasons. This means that lignite mining and industry need to keep operating, albeit at a much smaller scale; thus, prolonging the use of a low-cost indigenous energy source while at the same time providing a way to meet the need for energy security. However, in order to achieve this and yet maintain the pledge for zero CO_2 emissions, the only way to do so is by incorporating Carbon Capture, Utilisation and Storage (CCUS) technologies. Hence the IENE took the initiative in 2021/2022 and proposed the undertaking of a detailed study with the participation of interested companies to examine the role of CCUS in Greece, not just for power generation but across the entire industry spectrum.

The study which was carried out on a multi-client basis, was funded by a group of five companies including DEPA S.A., DESFA, Franco Compania Naviera S.A., HELLENIQ Energy and HEREMA S.A. The study entitled "CCUS Technologies in Greece – Prospects for implementation" runs into 350 pages and was conducted within an 8-month period. It was concluded in June 2023 with the active participation of the above partner companies. The present publication is an extended summary of the above study and outlines the key issues involved.

Although, the study, drew its inspiration from CCUS technologies as potentially applied to PPC lignite plants in West Macedonia, it goes well beyond that and examines a whole range of applications in Greece's industrial sector. As a result, IENE became interested once again in CCUS, an area of work which was first examined by the Institute in 2009 in connection with decarbonisation policies which were discussed at the time[1]. Hence, the actual scope of the study expanded considerably so as to include all different industrial and power generation emissions. In this context, the study examines in some detail the application of CCUS in industry and covers specific geographical areas such as the Aspropyrgos-Corinth axis in the south, Volos in the middle of the country, the west part of Thessaloniki and Alexandroupolis. The use of modern technology to track, capture and re-use CO_2 forms the central theme of this multi-client and multi-dimensional study.

CCUS carries considerable strategic value as a climate mitigation option and this has been recognised by international organisations such as the IEA and the European Union. It can be applied in a number of ways and across a range of sectors, offering the potential to contribute – directly or indirectly – to emissions reductions in almost all parts of the global energy system. Consequently, progress in developing and deploying CCUS technologies in one sector could have significant spillover benefits for other sectors or applications, including technological learning, cost reductions and infrastructure development. The four main ways in which CCUS can contribute to the transition of the global energy system to net-zero emissions include (a) tackling emissions from existing energy assets (power stations and industrial plants), (b)

[1] In December 2009, the IENE organised a well-attended workshop in Kozani with the support of the West Macedonia Region on Decarbonisation in West Macedonia. The workshop which was backed by ALSTOM and the IEA focused on CCUS technologies and their application in lignite-fired power generation units (the workshop proceedings in Greek are available through IENE).

providing a platform for low-carbon hydrogen production, (c) a solution for sectors with hard-to-abate emissions, and (d) removing carbon from the atmosphere.

CCUS may not be regarded as a new technology or concept, but it has been the subject of renewed global interest and attention lately, holding out the promise of a rapid scaling-up of investment, wider deployment and accelerated innovation over the last 5 years. The pipeline of new CCUS projects has been growing, underpinned by strengthened national climate targets and new policy incentives. At the same time, CCUS costs have been declining, new business models that can improve the financial viability of CCUS have emerged, and technologies associated with CO_2 use and carbon removal are advancing and attracting interest from policy makers and investors.

After years of declining investment interest, plans for more than 30 new integrated CCUS facilities have been announced since 2017, as noted by the IEA. The vast majority are to be found in the United States and Europe, but projects are also planned in Australia, China, Korea, the Middle East and New Zealand. Although some projects might fall by the wayside, the new investment plans for CCUS, if realised, will push the technology further along the learning curve, contribute to infrastructure development and further reduce unit costs.

Importantly, several of the planned projects go beyond the "low-hanging fruit" opportunities associated with natural gas processing to include less developed applications, including coal- and gas-fired power generation and cement production. There is also less reliance on Enhanced Oil Recovery (EOR), which has been a major driver of CCUS investment to date (16 of the 21 capture facilities in operation sell or use the CO_2 for EOR). Less than half of the planned facilities are linked to EOR, with a shift towards dedicated CO_2 storage options. Almost one-third of planned projects involve the development of industrial CCUS hubs with shared CO_2 transport and storage infrastructure.

The present study focuses on the means to tackle emissions from industrial sources in Greece and investigates the possibility of developing a platform for low-carbon hydrogen production. Moreover, it proposes a timeline type of roadmap for the implementation of CCUS in Greece for each stage of the value chain, especially with regard to the necessary steps towards establishing individual CCUS hubs across the country. The proposed path makes the CCUS technology an option for decarbonisation for the emitters without requiring them to construct expensive infrastructure or assume long-term liability for the stored CO_2. Potentially, five industrial-type hubs are proposed in addition to the Prinos underground storage facility. These include the Corinth-Aspropyrgos hub, the Thessaloniki hub, the Alexandroupolis hub, the Volos hub and the dedicated Ptolemaida Western Macedonia hub for power generation.

Finally, the report discusses the value chain which is important in the direction of effectively applying any CCUS application in Greece. Every main part of the value chain, that is to say CO_2 capture, transport, storage and utilisation, are considered and outlined with a view to provide the essential and required tools for action for any company interested to invest in CCUS.

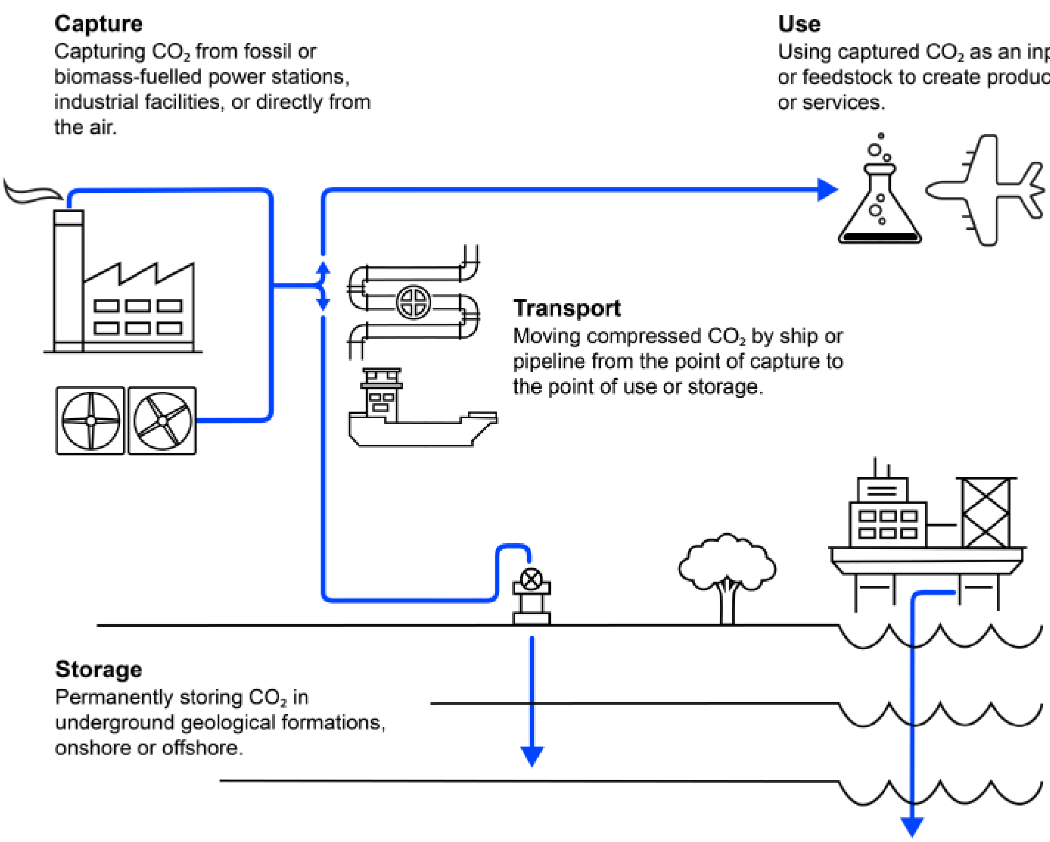
This study was prepared on a multi-client basis with the participation of companies sharing common interests and aspirations in their operations in a cleaner environment. Ultimately, it is hoped that this follow-up report will open the way for the companies individually or by way of group activity to pursue their investment plans within the net-zero framework and CCUS venture opportunities.

Chapter 1: CCUS and its importance

What is CCUS

Carbon capture, utilisation and storage (CCUS) refers to a suite of technologies that can play a diverse role in meeting global energy and climate goals. CCUS involves the capture of CO_2 from large point sources, such as power generation or industrial facilities that use either fossil fuels or biomass as fuel. The CO_2 can also be captured directly from the atmosphere. If not being used on-site, the captured CO_2 is compressed and transported by pipeline, ship, rail or truck to be used in a range of applications or injected into deep geological formations (including depleted oil and gas reservoirs or saline aquifers), which can trap the CO_2 for permanent storage. In the Net Zero Emissions by 2050 Scenario, the vast majority of the captured CO_2 is stored (Figure 1) (1).

Figure 1: The CCUS Technology outlined (2).



Today, CCUS facilities around the world have the capacity to capture more than 40Mt CO_2 each year. Some of these facilities have been operating since the 1970s and 1980s, when natural gas processing plants in the Val Verde area of Texas began supplying CO_2 to local oil producers for EOR operations.

Since these early projects, CCUS deployment has expanded to more regions and more applications. The first large-scale CO_2 capture and injection project with dedicated CO_2 storage and monitoring was commissioned at the Sleipner offshore gas facility in Norway in 1996. The project has now stored more than 20Mt CO_2 in a deep saline formation located around 1km under the North Sea.

Power plants fuelled by coal and gas continue to dominate the global electricity sector – they account for almost two-thirds of power generation, a share that has remained relatively unchanged since 2000 despite the advent of low-cost variable renewable sources. In absolute terms, power generated from fossil fuels has increased by 70% since 2000, reflecting the steady rise in global demand for power.

Coal remains by far the largest fuel source for power generation, at 38%, followed by gas at about 20%. In the world's fastest-growing economies, such as China and India, the coal-fired share of total generation is higher than 60%. While we saw a temporary dent in coal generation and higher shares for variable renewables due to the Covid-19 pandemic, these shares could return to historic trends as electricity demand fully recovers.

Power is the largest carbon emitter in the energy sector, creating almost 40% of global energy-related emissions. Despite the pressing need to confront the major causes of climate change, emissions in 2019 from the power sector were only slightly below their 2018 all-time high at 13.6Gt CO_2.

It is worth remembering that the Paris Agreement's goal is to keep the increase in global average temperature to well below 2°C above pre-industrial levels and, in doing so, to pursue efforts to limit the increase to 1.5°C. This has been incorporated into the critical energy-related UN Sustainable Development Goals, which in addition seeks to widen access to clean, affordable energy.

The global power sector is therefore expected to meet rising demand as access to electricity grows and to provide for a low-carbon future where end-use activities are increasingly electrified.

Despite the rapid expansion of renewable energy generation, the sheer scale of current power sector emissions and the vital role of electrification means that countries must urgently tackle their emissions from power to meet these global climate goals. In effect, the power sector has to dramatically reduce its carbon intensity.

To meet climate goals, policy makers need to address emissions from existing coal-fired power plants and those being built today but also from other emitting industrial facilities. Yet, under current policies stated by governments, while CO_2 emissions from the existing coal-fired fleet would decline by approximately 40%, annual emissions would still amount to 6Gt CO_2 per year in 2040. Significant additions to coal-fired capacity were still under construction at the start of 2023, highlighting the challenge ahead.

Meeting long-term climate goals without applying carbon capture, utilisation and storage technologies at scale in industrial and the power sector requires the virtual elimination of coal-fired power generation and, eventually, that of gas-fired generation as well, with significant early retirements and potential for stranded assets.

Concerning power generation, the young age of the global fleet of fossil-fuelled power plants means that about one-quarter of the existing fleet would be retired before reaching the typical 50-year lifespan. Almost one-third of all coal-fired capacity is less than ten years old, the vast majority of which is in Asia. Those kept in operation would likely see substantially reduced operating hours.

The IEA Sustainable Development Scenario outlines a major transformation of the global energy system, showing how the world can deliver the three main energy-related Sustainable Development Goals simultaneously. Under this scenario, carbon capture technologies play an important role in providing dispatchable, low-carbon electricity – in 2040, plants with these technologies generate 5% of global power. CCUS-equipped coal and gas plants become increasingly important for secure, sustainable and affordable power systems in the IEA Sustainable Development Scenario.

Meeting climate goals also means creating extremely flexible power and industry systems that can manage high shares of variable renewable power sources. Coal- and gas-fired power plants have been a major source of system flexibility, providing benefits essential to the operation of the electricity grid, such as inertia and frequency control. Carbon capture, storage and utilisation allows these plants to continue providing these benefits and meet long-term flexibility requirements, such as annual seasonality.

An emphasis on supporting system flexibility could see some CCUS-equipped coal and gas plants operating at relatively low load factors. However, the unique ability to achieve negative emissions through bioenergy with carbon capture and storage may mean that these plants run at high-capacity factors, even in a power system with high renewable shares. This could come at the expense of a reduced contribution to system flexibility but would support economics of scale in CO_2 transport and storage infrastructure and maximise climate benefits.

Including carbon capture, utilisation and storage in the portfolio of technology options can reduce the total cost of power and industrial systems transformation. Carbon capture technologies become more competitive in the power system when their flexibility, reliability and carbon intensity are fully valued.

Additionally, CCUS technology can have significant applications in other industries such as the cement industry, one of the most carbon-intensive sectors globally, where it can play a crucial role in reducing carbon emission. Cement production is a major source of CO_2 emissions due to the chemical transformation of limestone into clinker and the energy-intensive nature of the process. CCUS can capture CO_2 emissions directly from cement kilns and other sources within cement plants, preventing a substantial amount of CO_2 from entering the atmosphere.

Likewise, CCUS can play a vital role in the steel industry, particularly in mitigating carbon emissions associated with the production of steel. Captured CO_2 in the steel industry can be used in chemical processes or converted into valuable chemicals and materials or in some cases, CO_2 can be used in carbonation reactions to produce construction materials or other products.

Capturing CO_2

Much of the literature on CCUS classifies capture technologies into three broad categories: (a) **post-combustion**, (b) **pre-combustion**, and (c) **"oxy-fuel" combustion**. Each of these categories includes multiple variants related to the specific process by which CO_2 is separated from other compounds and isolated for further treatment and storage, either permanently or temporarily, prior to some beneficial use.

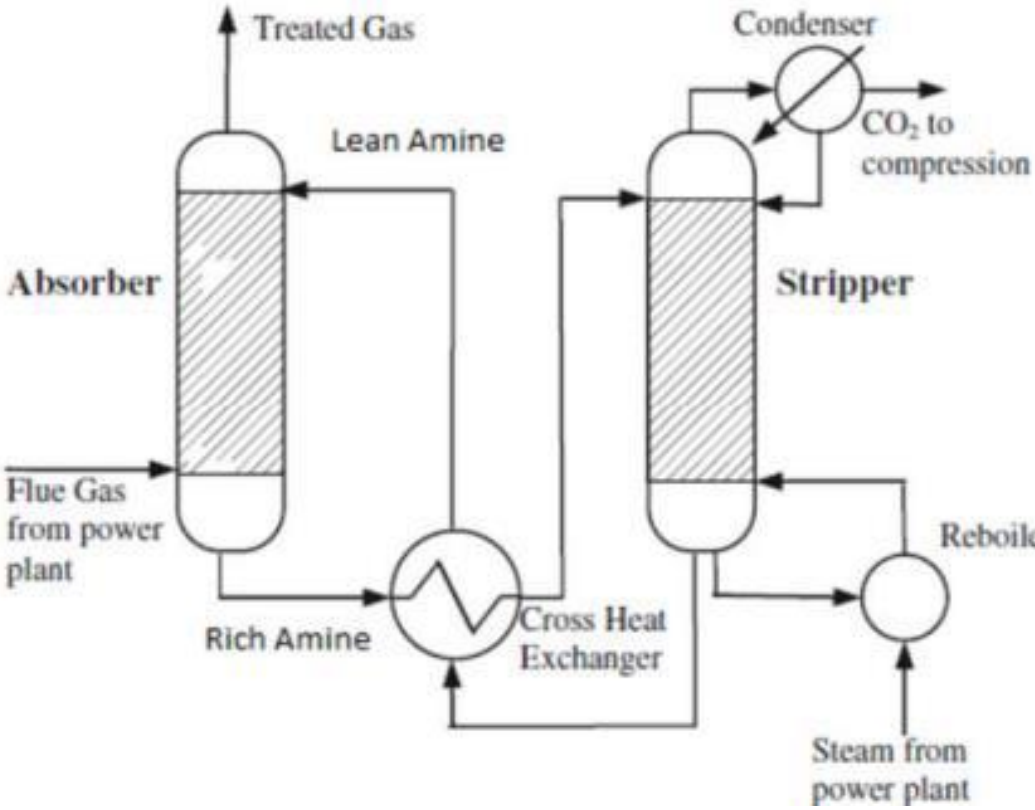
In post-combustion CCUS, CO_2 is captured from the flue gases produced by combustion of fuels with air. Air is mostly nitrogen (N_2) and, therefore, the flue gas contains large amounts of N_2 and nitrous oxide (itself a potent GHG) in addition to CO_2 and water vapor. Because it is not feasible to capture and prevent the release of the entire volume of flue gas, the CO_2 must be separated from the combustion flue gas. This is most often accomplished by passing the flue gas through a material that can capture the CO_2. The material can be either a liquid solvent or a solid sorbent that is capable of trapping the CO_2. The remaining gases are released to the atmosphere.

Liquid solvents are most often used for post-combustion capture, while physical sorbents are preferred for pre-combustion capture. The CO_2-laden solvent is further treated with heat or pressure to release the CO_2 as a stream of nearly 100% CO_2 that is cooled and compressed for use or storage. The purged or "clean" solvent is then recycled and used to capture more CO_2 (Figure 2). The energy required to separate the CO_2 from the solvent is the largest contributor to the energy penalty and added operating cost of CCUS systems, although the equipment required for CO_2 capture also adds substantial capital cost. The two CCUS plants in the western hemisphere, the Petra Nova Carbon Capture Project in Texas and the Boundary Dam CCUS Plant in Saskatchewan, Canada, use post-combustion sorbent capture technology.

Emerging technologies for post-combustion capture include cryogenic separation, membrane separation, and pressure/vacuum swing adsorption. So far, these technologies have been used primarily in applications other than electricity generation (e.g. natural gas processing), and none have progressed beyond the demonstration phase of development. Figure 2 shows the process for CO_2 recovery from flue gas with chemical absorbents.

In pre-combustion CCUS, the fuel is reacted with oxygen (O_2) to produce a "synthesis gas" or "fuel gas" composed of carbon monoxide (CO) and hydrogen (H_2). The CO is further processed with steam to produce CO_2 and more H_2. The CO_2 is separated with sorbent-based processes similar to the solvent absorption process used in post-combustion capture. The remaining H_2-rich fuel is then used to produce the desired heat or mechanical work in a boiler or combustion turbine.

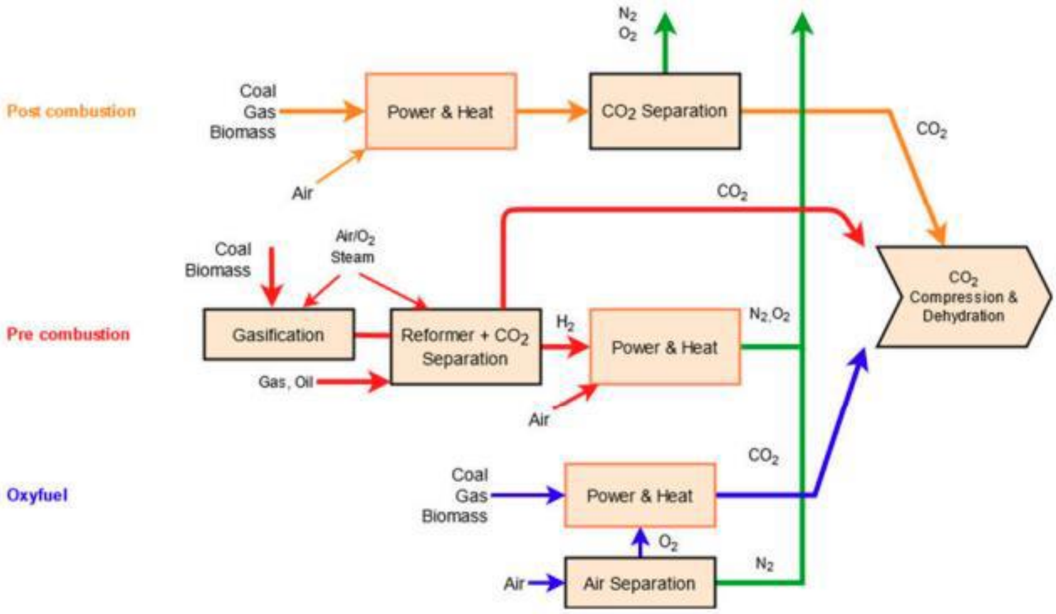
Figure 2: CO_2 recovery from flue gas with chemical absorbents (3).



This pre-combustion process is the basis for coal-fired integrated gasification combined cycle (IGCC) plants such as the planned, but never operational, Kemper Project in Mississippi. The energy penalty and additional cost results from both the fuel processing step and the capture and sorbent regeneration system.

Oxy-fuel combustion uses pure O_2 for combustion rather than air, producing a flue gas composed almost exclusively of water vapor and CO_2. The CO_2 is then captured directly with little further treatment. Here, the energy required for the production of O_2 for combustion is the largest source of the energy penalty. This technology has been tested at pilot scale in a few locations, including the NET Power Test Facility in Texas. An emerging technology related to oxy-fuel combustion is chemical looping, where the O_2 for fuel combustion is supplied not by gaseous O_2 but by fine particles of metal oxides or other materials. A concentrated stream of CO_2 is produced, and the reduced form of the metal is re-oxidised for recycling into the process. Figure 3 provides simplified process diagrams for each of the three major categories of CCUS.

Figure 3: CCUS Technology simplified process diagram (3).



Transporting CO_2

Once CO_2 has been captured from a generating facility (power generation or industrial source), it must be transported to a location where it will be used or stored. For efficient transport, CO_2 must be compressed into a liquid state at a pressure of about 100 times atmospheric pressure, or 10 times the pressure of a typical liquid propane gas tank. The liquid can be transported through pipelines or via ship to another location for storage or use.

In the United States, compression and transportation of CO_2 for commercial use is routinely performed through roughly 50 individual pipelines with a combined length of over 4,500 miles. The vast majority of this network supports EOR operations and is concentrated in the Midwest. Most of the CO_2 transported by these pipelines is from geologic (e.g. natural gas production) rather than anthropogenic sources. Almost all of the large-scale CCUS facilities currently in operation globally rely on pipelines to transport CO_2 from source to storage sites.

The current US network of CO_2 pipelines carries approximately 68Mt of CO_2 per year. In comparison, decarbonization scenarios that include CO_2 capture may require transporting many hundreds or even thousands of million metric tonnes. A recent study by the National Academies suggests the need for approximately 10,000 miles of “trunk lines” by 2035 to carry up to 250Mt per year.

Given the potential need for substantial new pipeline infrastructure to carry captured CO_2, studies have assessed the possibility of using existing natural gas pipelines for CO_2 transport. An additional consideration for transporting CO_2 is the lack of clear regulatory authority over the current transport network. Federal regulation of pipelines carrying dense liquid CO_2 is largely limited to safety under the Pipeline and Hazardous Materials Safety Administration. Neither FERC nor the Surface Transportation Board has exercised price regulation jurisdiction over CO_2 pipelines. Different definitions among regulatory bodies have caused confusion about jurisdiction.

As mentioned, in the United States, there are some pipelines used for transporting CO_2 for various purposes, including EOR and geological storage. These pipelines transport captured CO_2 from industrial sources to oil fields for EOR or to geological formations for long-term storage.

However, in Europe, including Greece, the focus has traditionally been on reducing or eliminating carbon emissions through the closure of plants and transitioning to renewable energy sources, rather than on large-scale CO_2 transportation and storage. Europe has been investing in carbon reduction strategies, renewable energy deployment, and policies to address net-zero targets.

Regarding Greece, the geographical constraints and differences in industrial landscape compared to the United States may make large-scale CO_2 pipeline infrastructure a lot less likely. Greece is a smaller country with different industrial profiles and priorities. The feasibility and relevance of CO_2 pipelines in Greece would depend on factors such as the country's industrial emissions, proximity to potential storage sites, and government policies.

While Greece may not have the same need or conditions for extensive CO_2 pipeline networks as some regions in the United States, it can still pursue other strategies for transporting and handling CO_2 emissions.

CO_2 storage

Effective long-term storage of CO_2 requires that it will be prevented from being re-released into the environment. Three main technologies are currently under investigation for storing CO_2 for a period long enough to be considered permanent (i.e. hundreds to thousands of years): (a) geologic storage, (b) ocean storage, and (c) mineral carbonation. Each of these technologies is in different stages of development and use. Geologic storage is the most well-developed method for storing CO_2 and the only one that has been used at commercial scale.

Injecting CO_2 into deep geological formations uses technologies that have been developed for and applied by the oil and gas industry for many years. Selection of CCUS sites can take years and millions of dollars that can be lost if the site is determined to be inadequate. It is possible to reduce the risk of selecting inadequate sites through an inexpensive and rapid assessment of CCUS reservoir viability. This assessment can be performed before drilling by analysing volatiles (e.g. CO_2, gas, oil) in rock samples from preexisting wells even if they are decades old. Doing so allows the assessment of past fluid leakage and migration and informs the site selector about the probability of leakage in proposed CCUS reservoirs before final site selection and drilling.

For new wells, volatiles analysis of materials can be performed rapidly to help guide the go/no-go decision on continuing investment. The US Department of Energy has been successful in reducing the cost of developing solar facilities using a similar method through its Sunshot program. The early assessment process can reduce the time and cost of developing carbon sequestration sites. While it is possible to reduce the cost of developing sequestration sites now, more research will be needed to expand the availability of sequestration locations. CO_2 has a lower density than water;

as a consequence, the presence of an overlying, thick, and continuous layer of silt, clay, or mineral deposits is the single-most important feature of a geologic formation that is suitable for geological storage of CO_2.

Chemical changes, such as mineral carbonation, may also occur with geologic storage, but only over much longer time-scales that are enabled by robust physical isolation. Using CO_2 for EOR is also a form of geologic storage. Injecting captured CO_2 into the ocean at great depth has the physical potential to store vast quantities of carbon, as much as hundreds of years of US power sector emissions at current rates. To date, this technology has not been tested at any appreciable scale. It currently exists only in the form of analysis, modelling, and preliminary research. Most proposals for ocean storage assume injection at greater than 3,000 meters depth, at which point CO_2 is denser than sea water and would, therefore, sink, rather than rise to the surface and re-enter the atmosphere.

This solution would require creation of an extensive pipeline network to transport the captured CO_2 either to ports where it could be transferred to ships for the final disposal at depth or directly to an offshore disposal point. Beyond the technical challenges and financial investment needed, ocean storage faces issues regarding potential environmental consequences, public acceptance, the implications of existing laws, safeguards and practices that would need to be developed, and gaps in our current understanding of ocean CO_2.

Another nascent decarbonization technology is “mineral carbonation,” which involves reacting CO_2 with metal oxides such as magnesium and calcium oxides to form carbonates. Carbonation, also known as “mineral storage,” can be considered both a storage and utilization option. The latter applies if the intended application of the carbonates goes beyond storing CO_2 to use as a material, for example, in the construction industry. Mineral storage can occur either in situ, in which case it is similar to geologic storage, or ex situ.

In either case, mineral storage of CO_2 is appealing because there is an abundance of naturally-occurring materials that could be used for this purpose, as well as the presumed near-permanence of storage of CO_2 in a stable, solid form. Public acceptance of ex situ mineral storage is likely to be high, because it is easy to verify that carbon has indeed been permanently stored. To date, only one large-scale in situ mineral storage project is in operation in Iceland.

On the other hand, as proposed by IENE in its recent study[2] and described fully in Chapter 5 of this publication, a temporary storage of CO_2 in steel tanks can become a part of the CCUS value chain. Temporary CO_2 storage typically refers to the capture and storage of carbon dioxide emissions for a limited period before they are either permanently sequestered or utilised in some way. This concept can be part of a broader CCUS strategy. IENE's proposal for such an approach is because the benefits of temporary CO_2 storage in steel tanks include flexibility in managing the timing of transportation and storage, which can be important for optimising costs and logistics.

Utilisation of CO_2

There are many potential beneficial uses of CO_2 from a CCUS facility, ranging from industrial refrigeration to food and beverage preparation. Currently, the most significant use by far is for EOR. The value of CO_2 to the end-user is of the greatest interest, because the revenues generated by selling CO_2 are an economic lever that can promote investment in CCUS plants.

"[2] "CCUS Technologies in Greece – Prospects for implementation", June 2023

Chapter 2: CCUS in Greece

Emissions in Greece

Greece may not be renowned for its heavy industry when compared to some of its European counterparts. Nevertheless, beneath the surface lies a complex industrial landscape that significantly contributes to emissions across various sectors. These sectors include the production of cement, chemicals, metal and steel industry, mining (aluminium production and until recently nickel), and the ever-increasing prevalence of motor vehicles. Additionally, power generation remains a critical source of emissions, primarily due to its reliance on conventional fossil fuels such as lignite and gas.

The cement industry, integral to construction and infrastructure development, plays a pivotal role in Greece's economy. However, it also bears a substantial environmental footprint, notably in terms of carbon emissions and resource consumption. Similarly, power generation, greatly reliant on fossil fuels, contributes significantly to greenhouse gas emissions and air pollution, impacting both the local environment and global climate.

The chemical sector and oil refining though crucial for various manufacturing processes, poses environmental challenges related to gas emissions. Steel and aluminium production are two other industrial activities which generate substantial emissions.

This intricate web of industrial activities and their environmental consequences underscores the pressing need for Greece to address its emissions profile and hence CCUS can be seen as a suitable mechanism to combat industrial emissions that can be tracked, captured and stored underground.

GHG Emission Trends in Greece

According to Greece's latest Emissions Inventory Report (2022), GHG emissions (without LULUCF) amounted to 74.84Mt CO_2 eq. in 2020, as shown in Table 1, recording a decrease of 27.66% compared to 1990 levels (4). If emissions/removals from LULUCF were to be included, then the decrease would be 30.06%.

Table 1: Total CHG emissions in Greece (in kt CO_2 eq.) for the period 2005-2020 (4).

	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
A. GHG emissions per gas (excluding LULUCF)																
CO_2	113.888,97	112.419,54	114.545,69	111.080,37	104.319,84	97.354,15	94.505,23	91.392,59	81.713,26	78.639,62	74.927,63	71.364,16	74.845,05	71.781,99	65.756,23	55.610,28
CH_4	11.407,33	11.482,28	11.362,41	11.241,70	10.864,03	11.082,19	10.936,97	10.776,02	10.533,54	10.340,35	10.145,94	9.797,52	10.096,52	10.217,07	9.991,41	9.685,20
N_2O	5.942,35	5.773,55	5.881,91	5.635,19	5.271,06	5.471,60	5.223,91	4.796,84	4.496,35	4.294,70	4.226,87	4.282,94	4.343,59	4.260,64	4.249,71	4.264,37
HFC	5.078,03	2.723,63	3.246,63	3.712,35	4.036,02	4.467,76	4.747,22	5.153,36	5.740,51	5.842,57	5.999,45	6.223,77	6.177,73	5.917,00	5.464,57	5.122,68
PFC	91,51	87,21	103,04	118,95	91,35	129,44	110,53	147,77	172,56	134,63	119,52	135,17	125,79	135,31	137,10	148,15
SF_6	6,15600	7,98000	9,46200	7,18200	5,01600	5,85960	5,13000	5,04857	5,15117	4,92154	5,06042	5,20201	5,01111	4,94269	4,92057	4,93861
Total	**136.414,35**	**132.494,19**	**135.149,15**	**131.795,74**	**124.587,31**	**118.511,01**	**115.528,99**	**112.271,63**	**102.661,38**	**99.256,79**	**95.424,48**	**91.808,76**	**95.593,70**	**92.316,96**	**85.603,94**	**74.835,61**
B. GHG emissions/removals from LULUCF																
CO_2	-3.308,21	-3.338,38	-1.826,78	-3.019,05	-3.103,80	-3.076,99	-3.166,00	-3.149,19	-1.614,72	-150,80	-3.745,52	-3.521,90	-3.282,72	-4.066,24	-3.164,36	-3.987,55
CH_4	10,54	20,96	321,27	43,55	46,16	16,41	17,81	43,71	16,00	9,40	10,81	31,67	18,55	19,42	77,68	18,71
N_2O	14,76	16,44	42,11	20,12	20,80	17,50	16,93	19,36	16,55	15,63	15,52	16,96	15,73	15,95	20,84	15,83
Total	**-3.282,91**	**-3.300,98**	**-1.463,40**	**-2.955,37**	**-3.036,83**	**-3.043,08**	**-3.131,25**	**-3.086,12**	**-1.582,16**	**-125,78**	**-3.719,19**	**-3.473,26**	**-3.248,44**	**-4.030,87**	**-3.065,85**	**-3.953,00**
C. GHG Emissions from International Transport																
CO_2	11.815,09	12.727,53	13.103,79	12.862,32	11.147,83	11.373,02	11.652,07	9.727,87	9.382,76	8.878,27	8.657,31	8.664,95	10.401,69	10.995,10	12.239,22	6.744,60
CH_4	19,89	21,52	22,09	21,68	18,35	19,06	19,56	16,00	15,09	13,22	12,52	12,06	15,12	15,62	17,92	11,15
N_2O	223,68	235,55	227,13	216,42	196,01	206,56	195,71	167,63	171,56	160,30	172,75	175,45	198,25	197,32	227,54	169,19
Total	**12058,66**	**12984,61**	**13353,01**	**13100,42**	**11362,19**	**11598,64**	**11867,34**	**9911,50**	**9569,40**	**9051,78**	**8842,57**	**8852,46**	**10615,06**	**11208,05**	**12484,68**	**6924,94**

Carbon dioxide emissions accounted for 74.31% of total GHG emissions in 2020 (without LULUCF) and decreased by 33.35% from 1990. Methane emissions accounted for 12.94% of total GHG emissions in 2020 and decreased by 13.18% from 1990, while nitrous oxide emissions accounted for 5.70% of the total GHG emissions in 2020 and decreased by 43.00% from 1990. Finally, f-gases emissions (from production and consumption) that accounted for 6.89% of total GHG emissions in 2020 were increased by 24.91% from 1995 (base year for F-gases).

GHG emissions trends by sector for the period 2005-2020 are presented in Table 2. Emissions from Energy in 2020 accounted for 68.98% of total GHG emissions (without LULUCF) and decreased by approximately 33% compared to 1990 levels.

Table 2: Total GHG emissions in Greece (in kt CO_2 eq.) by sector for the period 2005-2020 (4).

Year	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Energy	107.254,72	105.947,54	108.192,82	105.296,11	100.327,90	93.148,01	92.027,48	88.303,56	77.926,11	74.490,58	71.186,14	66.966,27	70.257,34	67.303,30	61.252,94	51.622,90
IPPU	15.432,05	12.748,21	13.184,95	13.002,12	11.271,23	11.759,57	10.387,88	11.207,11	11.942,97	12.307,11	11.967,30	12.498,15	12.784,89	12.383,00	11.700,79	10.485,79
Agriculture	8.969,24	8.869,28	9.018,77	8.730,78	8.500,37	8.834,31	8.576,44	8.451,28	8.383,73	7.990,54	7.821,38	7.833,46	7.860,40	7.791,80	7.781,37	7.846,37
Waste	4.758,33	4.929,16	4.752,61	4.766,73	4.487,82	4.769,11	4.537,20	4.309,69	4.408,57	4.468,55	4.449,66	4.510,88	4.691,07	4.838,86	4.868,83	4.880,55
Total [1)]	**136.414,35**	**132.494,19**	**135.149,15**	**131.795,74**	**124.587,31**	**118.511,01**	**115.528,99**	**112.271,63**	**102.661,38**	**99.256,79**	**95.424,48**	**91.808,76**	**95.593,70**	**92.316,96**	**85.603,94**	**74.835,61**
LULUCF	**-3.282,91**	**-3.300,98**	**-1.463,40**	**-2.955,37**	**-3.036,83**	**-3.043,08**	**-3.131,25**	**-3.086,12**	**-1.582,16**	**-125,78**	**-3.719,19**	**-3.473,26**	**-3.248,44**	**-4.030,87**	**-3.065,85**	**-3.953,00**
Index per sector																
Energy	139,22	137,52	140,44	136,68	130,23	120,91	119,46	114,62	101,15	96,69	92,40	86,92	91,20	87,36	79,51	67,01
IPPU	136,84	113,04	116,92	115,30	99,95	104,28	92,11	99,38	105,90	109,13	106,12	110,83	113,37	109,81	103,76	92,98
Agriculture	87,34	86,37	87,82	85,02	82,77	86,03	83,51	82,30	81,64	77,81	76,16	76,28	76,54	75,87	75,77	76,41
Waste	97,81	101,32	97,69	97,98	92,25	98,03	93,27	88,59	90,62	91,85	91,47	92,72	96,43	99,47	100,08	100,32
Total [2)]	**131,86**	**128,07**	**130,64**	**127,40**	**120,43**	**114,56**	**111,68**	**108,53**	**99,24**	**95,95**	**92,24**	**88,75**	**92,41**	**89,24**	**82,75**	**72,34**

[1)] Emissions / removals from *Land Use, Land Use Change and Forestry* are not included in national totals

[2)] *Land Use, Land Use Change and Forestry* is not included

The majority of GHG emissions (47.43%) in 2020 derived from energy industries (i.e. power generation from lignite and gas), while the contribution of transport, manufacturing industries and construction and other sectors is estimated at 29.75%, 8.63% and 12.76% respectively. The rest 0.86% and 0.58% of total GHG emissions from Energy are derived from fugitive emissions from fuels and other (mobile). Within the fuel combustion activities, the only sector with increased emissions compared to 1990 is transport, showing an increase of 5.78%. Emissions from energy industries, manufacturing industries and construction and other sectors (i.e. residential, tertiary and agriculture sectors) had decreased by around 47.43%, 52.64% and 23.90%, respectively, compared to 1990. The decrease in the other sectors is noticeable during the recent years. Finally, fugitive emissions from fuels decreased by 63.48% for the period 1990-2020.

Emissions from Industrial Processes and Product use in 2020 accounted for 14.01% of the total emissions (excluding LULUCF) and decreased by 7.02% compared to 1990 levels. Emissions from IPPU are characterised by intense fluctuations during the period 1990-2020 reaching a minimum value of 10.39Mt CO_2 eq. in 2011 and a maximum value of 16.41Mt CO_2 eq. in 1999. The low value for 2011 is directly related to the effects of the economic recession whereas the maximum value is attributed to changes in industrial production and especially in HCFC-22 production. It should be noted that had it not been for the consumption of f-gases subcategory, the decrease of the recent years would have been much deeper.

Emissions from Agriculture that accounted for 10.48% of total emissions in 2020 (without LULUCF), decreased by approximately 23.59% compared to 1990 levels. Emissions reduction is mainly due to the reduction of N_2O emissions from agricultural soils, because of the reduction in the use of synthetic nitrogen fertilizers and animal population. The decrease in the use of synthetic nitrogen fertilizers is attributed to the increase of organic farming, the high price of fertilizers and the impact of initiatives to promote good practice in fertilizer use. The changes of the rest determining parameters of GHG emissions from the sector (e.g. crops production etc.) have a minor effect on GHG emissions trend.

Emissions from the Waste sector (6.52% of the total emissions, without LULUCF), increased by approximately 0.32% from 1990. Living standards improvement resulted in an increase of the generated waste and thus of emissions since 1990. However, the increase of recycling along with the exploitation of the biogas produced limits the increase of methane emissions. At the same time, emissions from wastewater handling have considerably decreased, due to the continuous increase of the population served by aerobic wastewater handling facilities.

The Land Use, Land-Use Change and Forestry (LULUCF) sector was a net sink of greenhouse gases during the period 1990-2020. The sink capacity of the LULUCF sector fluctuates between -0.13Mt CO_2 eq. and -4.03Mt CO_2 eq., showing fluctuations in trend. This is the result of the decrease of the sink capacity of the Cropland category on the one hand, and the increase of the sink capacity of the Forest Land category on the other.

CO_2 Capture and Transportation in Greece

Studies have shown that today the industrial CCUS deployment can potentially capture 30Mt and can be escalated to 4,000Mt by 2040 (5) (6). Until recently, in

Greece, coal combustion produced 39% of the country's gross CO_2 emissions (HAEE, 2019). Specifically, three active power plants (see Table 3) are associated with these large CO_2 emissions (7). Namely, the operating electricity power stations of Western Macedonia are the Agios Dimitrios, Kardia and Meliti stations and they are located in the industrial territory of Western Macedonia. However, according to the Greek National Energy and Climate Plan, the aforementioned power plants will be retired by 2023 and will be replaced by a new station, Ptolemaida V, which will potentially include CCS to its function (8).

Table 3: Emission parameters regarding the function of Greek power plants (7).

Power Plant	CO_2 Emissions (t/y)	CO_2 (%v/v)	T (°C)	Flow Rate (Nm^3/h)
Agios Dimitrios	6,840,000	12	151	571,831.00
Kardia	2,870,000	10,375	147.52	759,324
Meliti	1,410,000	12-14	65-96	786,133.61

The possibility of capturing CO_2 produced by Ptolemaida V has been explored within the STRATEGY CCUS project. As mentioned in the previous section, STRATEGY CCUS was a CCS scenario development project, in which Greece was involved through the Centre for Research and Technology Hellas (CERTH) as one of the 17 associated partners. Among the proposed scenarios, one of them suggests the capture of the estimated 4.5Mt of CO_2 per year, emitted by Ptolemaida V (9).

Up to date, no further CO_2 capture plans that concern Greek case sites have been introduced; nonetheless Greek Institutes and Organisations have actively participated in European projects that study and implement CO_2 capture technologies (Table 4).

Koukouzas and his associates, made an assessment for the transportation costs of CO_2 from a proposed 650MW coal-fired power plant using supercritical steam cycle and equipped with CO_2 capture technology, to selected saline aquifers as storage sites (10). The CO_2 capture technology selected for this scenario was the post-combustion technique of chemical absorption with amines. The authors, considering an average emission rate of 140kg/s CO_2 and an average capture rate of 90%, estimated that approximately 3.5Mt of CO_2 per year will be captured and available for storage (10).

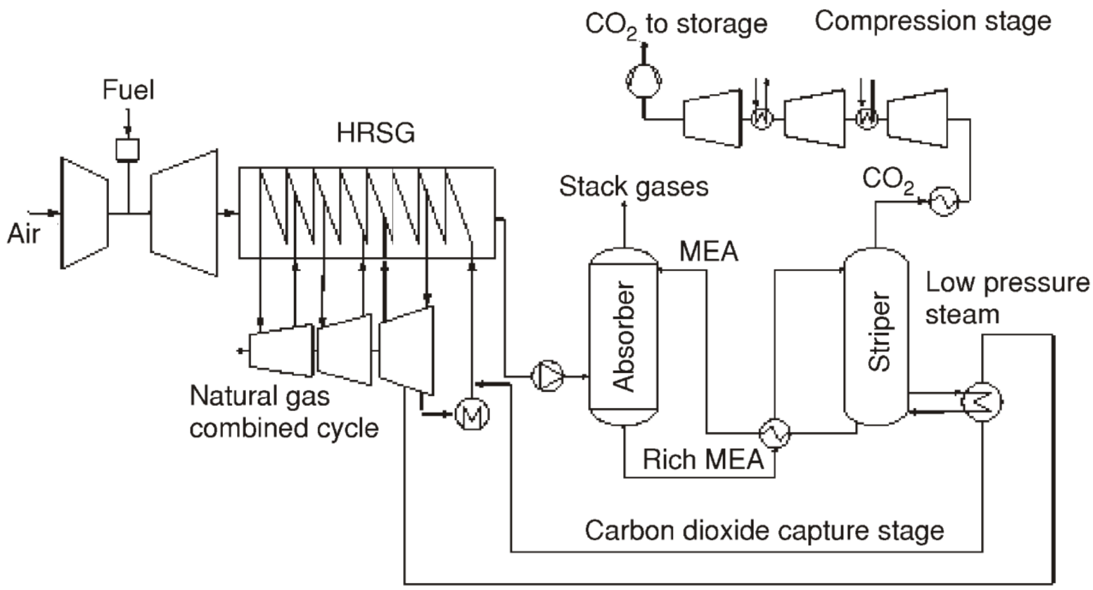
Table 4: List of European Projects in which Greece has participated.

Project Name	Leading European Country	Duration	Website
ASSOCOGS	UK	2003-2006	https://cordis.europa.eu/project/id/RFCR-CT-2003-00008
ENCAP	Sweden	2004-2009	https://cordis.europa.eu/project/id/502666
CAL-MOD	Germany	2010-2013	http://cal-mod-eu-projects.de/
COAL2GAS	Romania	2014-2017	http://coal2gas.eu/
SCARLET	Germany	2014-2017	http://www.project-scarlet.eu/wordpress/
ECCSEL	Norway	2015-2017	https://cordis.europa.eu/project/id/675206
CLARA	Germany	2018-2023	https://clara-h2020.eu/
STRATEGY CCUS	France	2019-2022	https://www.strategyccus.eu/
LEILAC2	France	2020-2025	https://www.leilac.com/
ConsenCUS	Netherlands	2021-2025	https://cordis.europa.eu/project/id/101022484
COALBYPRO	Greece	2017-2020	-
AC2OCEM	Germany	2021-2023	http://www.act-ccs.eu/

Furthermore, Koukouzas and his associated in 2006 examined the feasibility of capturing, transporting, and storing CO_2 from a natural gas (NG) combined cycle power plant in Northern Greece to the Prinos basin offshore oil reservoir (11). The capture method that was chosen for the scenario was the post-combustion CO_2 capture technology with amine scrubbing (i.e., via chemical absorption). The basic principle of amine scrubbing technology includes separating the CO_2 gas from the emissions from the heat recovery steam generator (HRSG) of the power plant, via chemical absorption with amines. The amines are on aqueous solutions, such as MEA, and they absorb the CO_2 gas with reversible chemical reactions (11) (12) (13) (14). The reversibility of those reactions allows the separation and recovery of CO_2 via heating, while the MEA can be reused for repeating the process (11).

The application of amine scrubbing capturing technology at the Komotini NG combined-cycle (NGCC) power plant has been simulated by Koukouzas and his associates in 2006 (11). The capturing process in this NGCC power plant is presented in the scheme below (Figure 4), and involves the following stages: (a) the flue gas passes through the heat recovery steam generators (HRSG) into the amine plant, where CO_2 is captured by the amine-based aqueous solution, and a CO_2 rich-stream is produced, (b) the CO_2 is separated, compressed, and cooled up to the required conditions (140bar, 32°C) for transportation via pipelines and storage to the geological reservoir.

Figure 4: Schematic representation of the CO_2 capture process via amine scrubbing in the NGCC power plant (11).



The evaluation of the proposed scenario revealed a general loss in energy production when CO_2 capture was included in the system. More specifically, the net power produced was reduced from 476MWe without CO_2 capture, to 395MWe with CO_2 capture. Similarly, the net plan efficiency was reduced from 52% to 43% (11). On the other hand, the total CO_2 emissions to the atmosphere was 504kg/MWh for NGCC without CO_2 capture, and only 50.4kg/MWh in the case including CO_2 capture via amine scrubbing, which is a significant advantage compared to the small energy losses. A drawback of the amine scrubbing capturing process that costs energy is the significant amount of the heating energy required, as well as the electrical energy for the subsequent compression of the captured CO_2 in order to allow its transportation via pipeline (11). Apart from the aforementioned preliminary assessment cases, as well as the STRATEGY CCUS Horizon 2020 project, CO_2 capture has yet to be implemented in a wide scale in Greece. Further research, funding and actions are needed for the implementation of such projects. In smaller scale, CO_2 capture will potentially be applied in companies from the Greek 90 industrial sector, such as TITAN SA cement company and Motor Oil Hellas, using the oxy-fuel method (15).

The transportation method of CO_2 from the source location to the storage site is selected considering the distance between them, the morphology of the surface, the location of the reservoir (onshore or offshore), as well as the quantity of carbon dioxide to be transported (16). The most common CO_2 transfer methods include road transportation, shipping, pipeline systems, or combination of the above. However, it is generally premised that the transportation via pipeline networks is the most efficient method, especially in economic terms (7).

In many cases, pipeline infrastructure may already be available for CO_2 transportation, due to the exploitation of gas and/or oil fields in the area. Such examples involve the oil and gas fields of Prinos basin or the nearby Epanomi gas field. Other already existing pipeline systems that could be utilised for onshore CO_2 transport include the national roadway network that connects Western Macedonia with the Balkan countries.

This network also provides access to the rest of Greece, as well as the seaports of Thessaloniki (140km from the Western Macedonia industrial zone), Kavala (291km), and Alexandroupolis (450km) to the east (North Aegean Sea), and Igoumenitsa (230km) to the west (Ionian Sea) (7) (17). More specifically, the ports of Thessaloniki and Alexandroupolis are already equipped with oil and gas terminals especially due to the proximity of industrial and gas storage facilities. Those terminal stations are able to support infrastructure for CO_2 transport (7) (17).

Another existing pipeline network that can be utilised for CO_2 transport is the Transadriatic pipeline of the Southern Gas Corridor. This network is 878km long and connects the Caspian countries to Greece, Albania, and Italy for the transmission of natural gas. The technology of simultaneous NG and CO_2 transportation through this pipeline system is still being developed, in order to increase the capacity of the pipeline system from the existing 10bcm/y to 20bcm/y (7) (17). Koukouzas and Typou conducted a preliminary assessment of the transportation of CO_2 emissions from sources such as the coal-fired power plants of Northern Greece, to nearby geological reservoirs (16).

The potential storage locations involved the saline aquifers of Pentalofos formation of the Mesohellenic Trough, the West Thessaloniki saline aquifer, the Prinos basin oil reservoir and saline aquifer (10). The authors created three scenarios: (a) the transportation of CO_2 emissions from Ptolemaida power plant to the Pentalofos saline aquifer, (b) the transportation from Meliti and Amyntaio power plants to the West Thessaloniki saline aquifer, and (c) the transportation from Kardia, Agios Dimitrios and Komotini power plants to Prinos oil reservoir and saline aquifer (10).

The scenarios included booster stations between the emission sites and the storage sites, in order to maintain the maximum production efficiency as the pipeline extended. They calculated the cost of the pipeline considering that the morphology of the surface would be a flat terrain (best scenario), and the pipeline lifetime over 50 years.

In general, the cost assessments were conducted considering specific factors required for the implementation of the transport process from power plants to different reservoirs. Three scenarios were examined:

- CO_2 from Ptolemaida power plant to Pentalofos saline aquifer, with 4Mt CO_2 emissions and 216Mt aquifer capacity, storing for 54 years. Costs include

€23.13MM for the pipeline, €5.97MM for booster station, and €0.37/tn CO_2 for storage.

- CO_2 from Meliti and Amyntaio power plants to West Thessaloniki saline aquifer, with ~7Mt CO_2 emissions and 420Mt aquifer capacity, storing for 60 years. Costs include €47.29MM for pipeline, €11.95MM for boosters, and €0.44/tn CO_2 for storage.
- CO_2 from Kardia, Agios Dimitrios, and Komotini power plants to Prinos basin reservoirs, emitting ~24Mt CO_2 with 1,240Mt combined reservoir capacity, storing for 51 years. Costs include €172.73MM for the pipeline, €17.92MM for boosters, and €0.41/tn CO_2 for storage.

All three scenarios demonstrate economic feasibility for CO_2 transport and storage, with varying costs and storage durations based on specific factors and reservoirs.

Table 5: Scenarios adapted by Koukouzas and Typou (2009) and data from the preliminary assessments by the authors concerning CCUS application in PPC's power plants in Ptolemaida, Kozani and Komotini area (16).

Scenario	**(a) Ptolemaida power plant/Pentalofos saline aquifer**	**(b) Meliti and Amyntaio power plants/West Thessaloniki saline aquifer**	**(c) Kardia, Agios Dimitrios and Komotini power plants/Prinos oil reservoir and saline aquifer**
Power plant emissions	4	~7	24
Storage site capacity (Mt)	216	420	1,240
Storage capability period (years)	54	60	54
Investment cost (€MM)	23.13	47.29	172.73
Operational cost (€MM)	0.63	1.42	4.00
Booster Station Investment Cost (€MM)	5.97	11.95	17.92

In 2011, Koukouzas and his associated studied the transportation costs of CO_2 via pipelines for three significant Greek geological storage sites in saline aquifers. They focused on a new 650MW lignite-fired power plant in Western Macedonia, designed for CO_2 capture (10). The three storage sites were Prinos, West Thessaloniki, and Mesohellenic Trough (Pentalofos) saline aquifers, all within a 200km radius of the power plant. The plant could emit around 140kg/s of CO_2, resulting in 3.5Mt available for storage annually. They used chemical absorption with amines for a 90% capture rate and calculated transportation costs based on the IEA Greenhouse Gas R&D Programme (Report Number: 2005/2 CO_2 storage: European Sector) (18). The pipeline construction and transportation costs calculated, are the following:

Table 6: Cost of pipeline-based CO_2 transport and geological storage in saline aquifers in Greece (10).

Site	CO_2 Storage Capacity (Mt)	Pipeline investment cost (M€)	Transport cost (€/t CO_2)	Annual transport cost (M€/y)
Prinos	1,350	52.3	2.15	7.7
West Thessaloniki	605	31.5	1.06	3.8
Mesohellenic Trough (Pentalofos)	216	29.6	1.00	3.6

In general, the transport cost, as well as the storage cost, depend on the location of the reservoir, and especially whether it is an onshore or offshore reservoir. More specifically, the costs increase significantly for the offshore locations, which is a noteworthy disadvantage.

However, the increased costs for the offshore reservoirs may be stabilised by other factors, such as existing pipeline networks, as mentioned above. For example, in the saline aquifer of Prinos offshore basin, the existing infrastructure used for oil and gas exploitation, such as drilling boreholes, platforms, and available pipeline network may contradict the increased costs (10) (18) (19).

Alternative transportation methods, such as CO_2 shipping, should be considered while CO_2 transportation sea corridors are expected to be introduced, as plans that provide midstream (transport, storage, wholesale) services have been proposed by the private sector. In particular, industrial cargo vessels will be able to transport over 1Mt of CO_2, while the overall aim is to reach 50Mt of CO_2 by 2035. The aforementioned target CO_2 amounts are planned to be safely realised under the storage and transportation at 8bar pressure (https://www.ot.gr/2022/05/06/englishedition/ceres-shipping-invests-in-a-fleet-of-60-ships-to-capture-carbon/).

Chapter 3: CO_2 Storage options in Greece

Underground storage sites are key in Greece's strategy to develop CCUS. However, as it will be explained in Chapter 5, it is not vital for these locations to be strictly in Greece since CO_2 shipment costs are not prohibitive and CO_2 could be transported to underground sites elsewhere in the Mediterranean or further afield.

The selection of underground storage sites in Greece, is based on technical and economic criteria, geology, the presence of wells drilled and the available seismic information, the vicinity to industrial activities emitting CO_2, and the proximity to transportation facilities such pipes and/or ports (Figure 5 and Figure 6).

Macedonia has the advantage to be near refining sites as well as near land and coastal transport hubs of Thessaloniki (Greece) to the east and Ballsh and Fier (Albania) to the west. Further, it can serve Albania, North Macedonia and Bulgaria. From a commercial point of view, the interconnections of Egnatia, Central Greece and Ionian roads network, the route of TAP natural gas pipeline from the northern boundary of Western Macedonia, the expected regasification stations in Thessaloniki, Kavala and Alexandroupolis, all indicate a significant strategic interest for the Regions of Macedonia.

Geographically, four (4) areas are of main interest for CO_2 subsurface storage and are situated in Western, Central and Eastern Macedonia. Especially, Western Macedonia is the largest sources of CO_2 in Greece due to the presence of the lignite power plants. Although the use of lignite was stranded, these plants continue to "burn" once more lignite and fuel oil until the time they will be totally replaced by natural gas.

The types of storage complexes include saline formations, oil and natural gas reservoirs, unmineable coal areas and organic-rich shales. Further south, the area of Volos in Central Greece represents an additional candidate for storage in basalts because of the vicinity of the cement industry and of the project of FSRU facility close to the port of Volos and the National Gas Grid. However, this basaltic site will require more studies for the understanding of the process. Hence, the most plausible storage complexes are:

- the Mesohellenic Trough in Western Macedonia, with storage plays at shallow depths and possible gas reservoirs at deeper parts of the trough
- the West Thessaloniki large geothermal basin and the Epanomi field in Central Macedonia with known discoveries of gas and CO_2 fields
- Prinos and S. Kavala in Eastern Macedonia, with a series of partially deleted oil and gas reservoirs.

All three (3)complexes satisfy the strict criteria of selection: (a) a confining zone that includes a thick (or several) sealing layer(s) above the storage zone, separating the stored CO_2 from drinking water sources and the surface; (b) adequate integrity within the storage formation and sealing layers; (c) sufficient porosity and permeability to store large amounts of CO_2; and (d) are at supercritical depth to allow for storage of concentrated CO_2. The basin of Florina in Western Macedonia should serve as a useful case of CO_2 natural leakage to the surface.

A detailed analysis follows, of the above three main complexes. This shows that Greece has a number of suitable geological formations that can accommodate substantial CO_2 volumes for capture and storage needs for several years.

Figure 5: The network of gas pipes, ports and planned FSRU facilities in Greece. The facilities at the northern part of the country target the Balkan countries and show the importance of this geographical position for the energy planning of northern Greece.

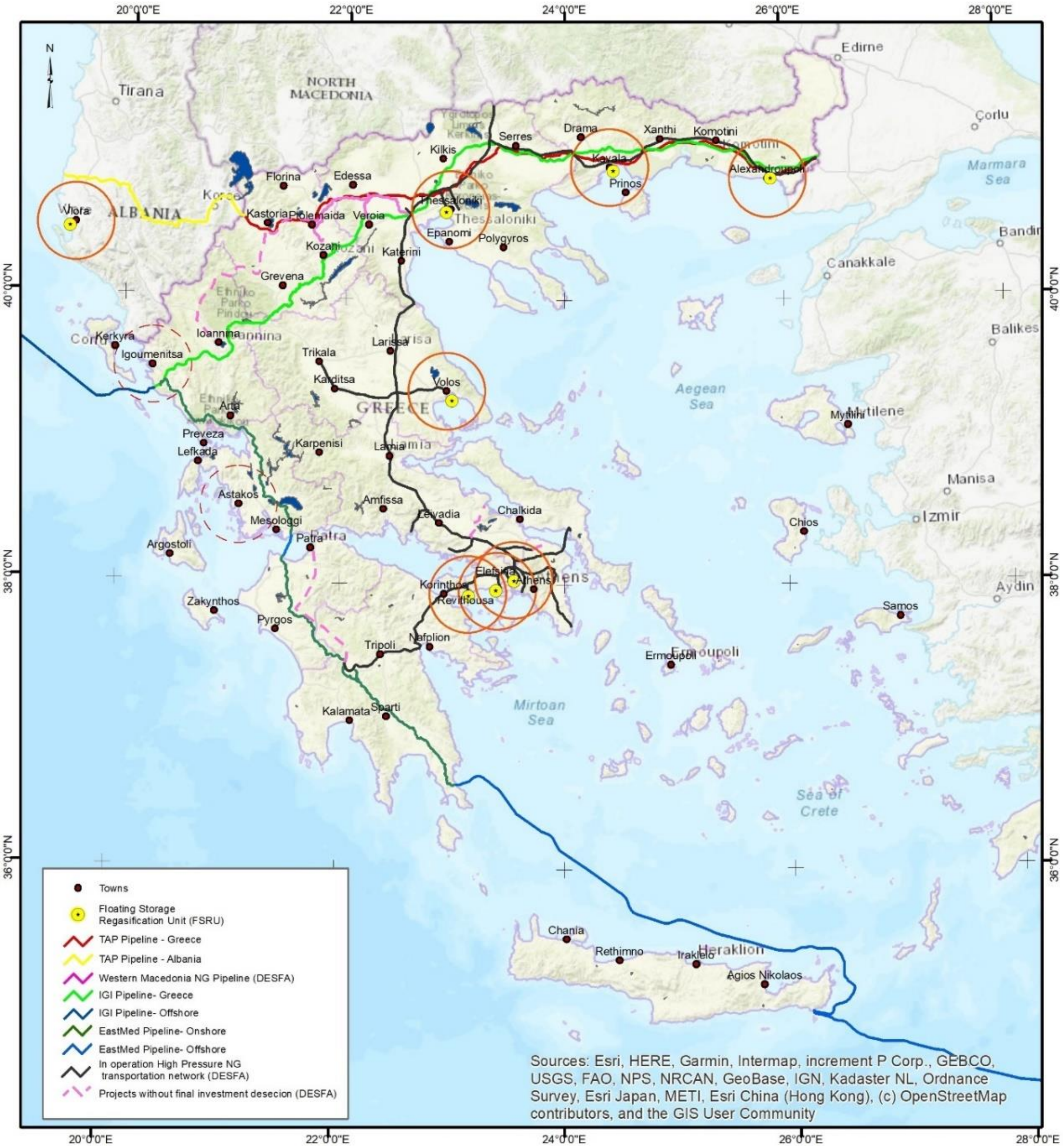
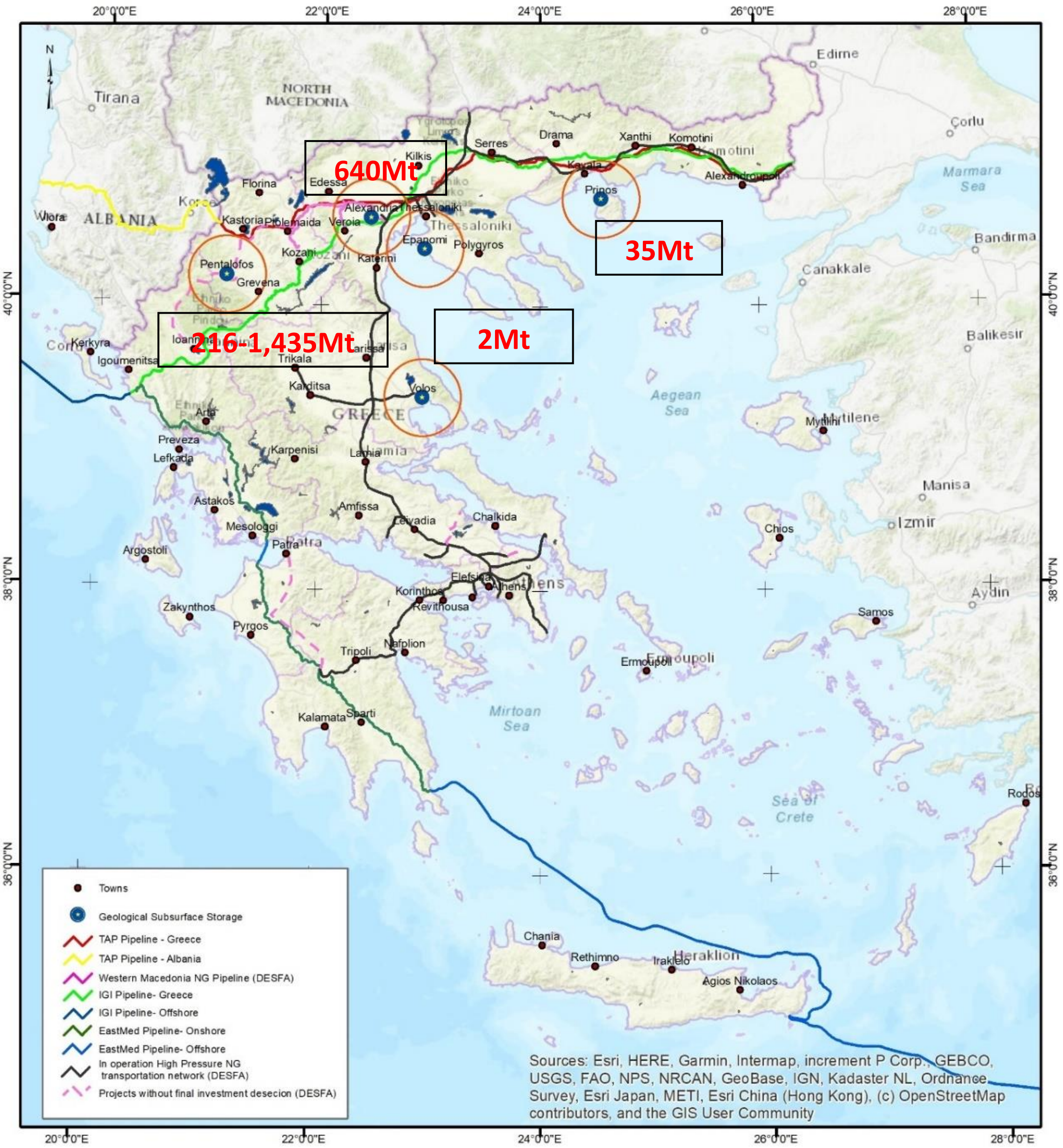


Figure 6: Underground storage locations in Greece with estimated storage capacity in Mt of CO_2.



Western Macedonia

The Mesohellenic Trough

From a geological and geophysical point of view, the Mesohellenic Trough had always been a centre of academic research for the exploration of a possible natural gas reservoir at depths of 3,000 meters. Possible gas reservoirs could contribute to balance the energy deficit due to the progressive lignite phase-out in the coming years. Two processes of storage are envisaged, the in-situ injection of CO_2 and the mineralization of CO_2 within the sandstones.

- <u>In-situ CO_2 injection:</u>

The Mesohellenic Trough (Figure 7) provides an appropriate geological environment for CO_2 injection:

- the size of the basin ranges from 5,000-25,000km^2. It is the largest and most important basin of the last orogenetic stage - "molassic-type" basin of Greece.
- the thickness of the sedimentary layers ranges from 1.5-3.5km,
- three (3) geological formations satisfy the CO_2 storage criteria: Eptachori (storage), Pentalofos (repository), Tsotili (caprock).
- the possible existence of gas, in the deeper layers of the trough, supports the presence of a petroleum system.
- the area is tectonically relatively stable.
- the proximity to industrial sources of CO_2 emission such Ptolemaida to the east and Florina to the north (less than 50km in straight line).

- <u>Mineralisation</u>

In the case of mineralization of CO_2 in sandstones, a saturated brine should react with the minerals causing their dissolution, and subsequently increase the acidity and the content of cation. Geochemical simulations extrapolated at 10,000 years, with T=70°C and P=150bars, reveal a possibility for long-term CO_2 mineralogical sequestration in the Pentalofos and Tsotyli formations. These reactions are generally characterised by a slow rate of chemical changes and the process should normally follow the injection "precursor" process (in-situ CO_2 injectivity).

Figure 7: Geological map of the Mesohellenic Trough and stratigraphy of the area with indications of the storage space (Res=reservoir, Cap=caprock) (20) (21).

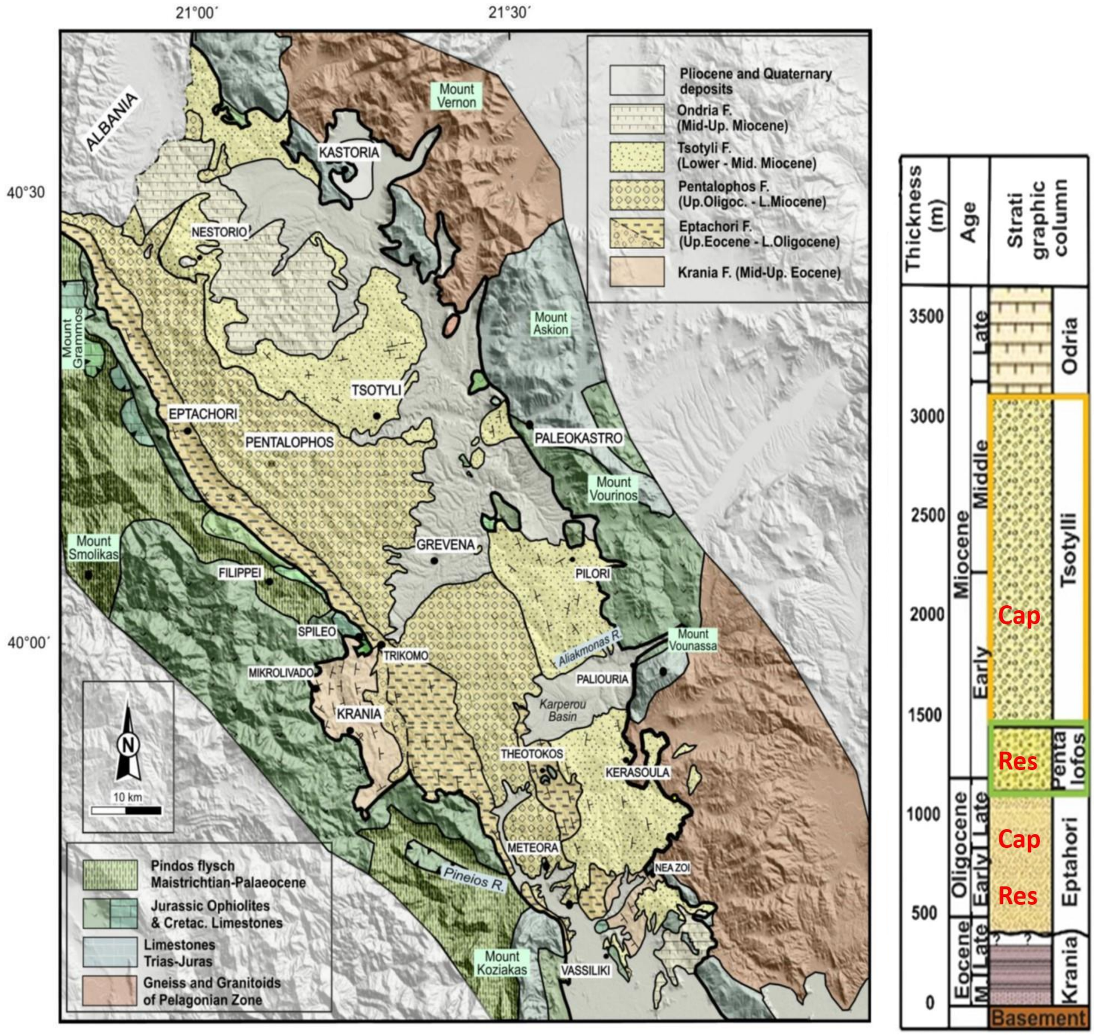


Table 7: Mesohellenic Trough properties.

Mesohellenic Trough
CO_2 storage space: The Eptachori formation consists of marls of Upper Oligocene above sandstone and conglomerates and corresponds to a possible site storage of CO_2, (22) (23). The sedimentary phases include deltaic conglomerates, alluvial debris, sandstones, and clays of underwater turbidites as well as sandy continental shelf sediments. These are basic components of a storage environment.

CO_2 repository: The Pentalofos formation consists of alternating breccia with sandstones (Tsarnou conglomerate) and could become, at regional level, a repository for CO_2.

Cap-rock: The Tsotyli formation consists mainly of silicious marls with interlayers of sandstones, conglomerates, and clastic marly limestones. This formation, due to its watertight properties could potentially be used as a cap rock.

Storage capacity: The lowest part of the Pentalofos Formation, at depths close to 2,500m offers the maximum storage capacity estimated at 216Mt CO_2. The total storage capacity in the Pentalofos reservoir (members Tsarnos and Kallonis) was estimated at about 5Gt CO_2 (24). CO_2 storage can be achieved via in situ injections within the pores of the sandstones or directly in saline aquifers within the sandstones of Pentalofon.

Depth of the formations: The deepest CO_2 storage location corresponds to the base of the Tsarnos member in 2,544m depth in a rather cold basin (estimated geothermal gradient of 35°C/km) maintaining the CO_2 in a supercritical state. Note the presence of two hypocentres which can serve as two distinct compartments of storage.

Porosities: In-situ injection in the pores of the sediments of Pentalofos and Eptachori can expand at a surface area of 3,813km^2 with average porosities of around 15%. However, these porosities are known from the wells drilled at the borders of the basin and not from the centre of the basin.

Structural setting: Anticlines work as structural traps for CO_2 storage.

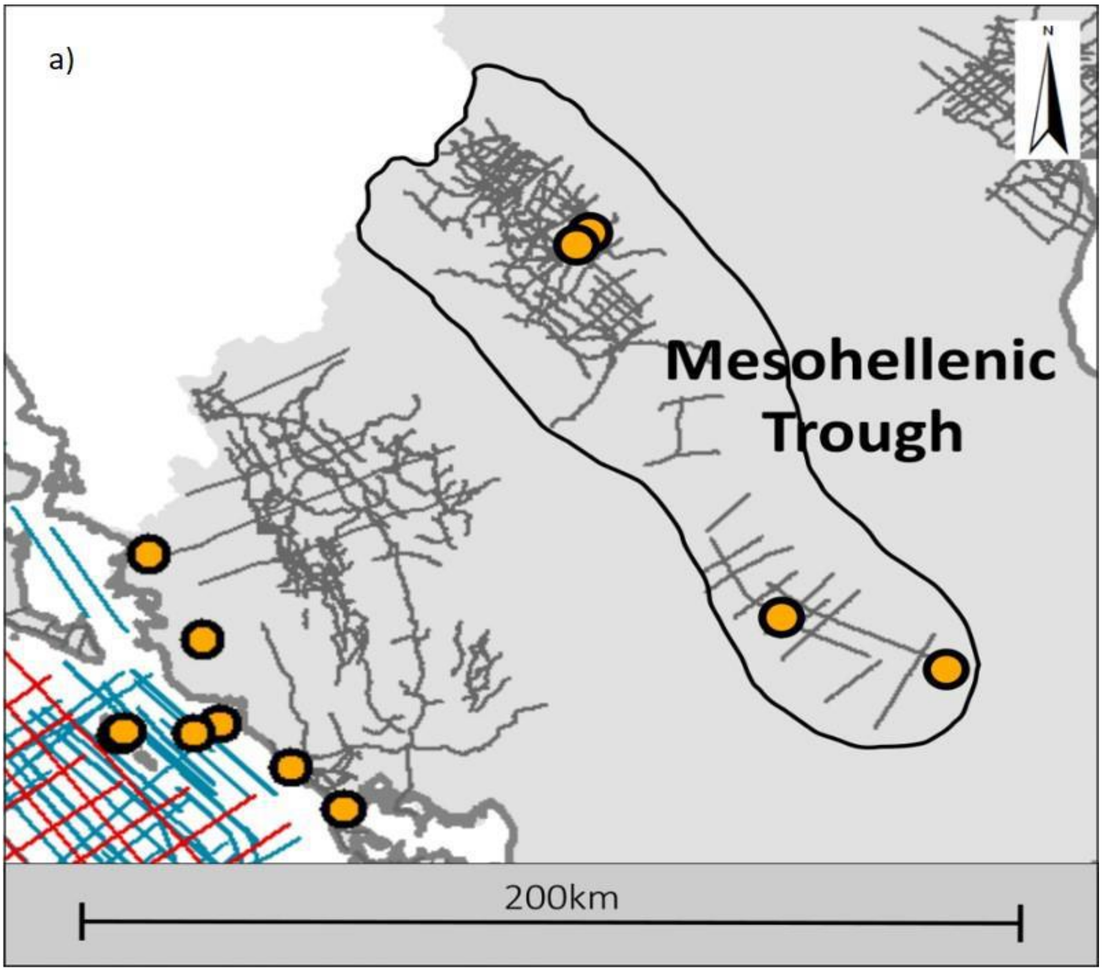
Seismicity: Geophysical data reveal the presence of several faults within the basin, some of which are still considered active (21).

Static 3D model: A static 3D model, based on the interpretation of the existing dense 2D seismic network (including 1,086km) and the drilling data is missing but could provide an accurate estimate of the surface, the vertical extent of the reservoir and the porosity for CO_2 storage purposes. Data is available in the libraries of HHRM (25) (Figure 8).

Table 8: Summary data for the Mesohellenic Trough storage.

Summary	Mesohellenic Trough
CO_2 storage thickness (m)	Eptachori + Pentalofos: 600
Cap-rock thickness (m)	1,500
Storage capacity (Mt CO_2)	216
Storage space (km^2)	3,813
Aquifer depth (m)	2,500 with two depocenters
Porosity (%)	15
Permeability (mD)	?
Structural setting	anticlines
Pore volume (m^3)	285,000
Hydrocarbons presence	possible at depth (shales)
Cap-rock quality	good
Injectivity	2 confining zones
Measured T/P	70°C/150bars
Leakage risk	low
Seismicity	low

Figure 8: a) Potential geological areas for CO_2 storage in the Mesohellenic Trough and hydrocarbon exploration wells on the west coast of Greece with indicative distance from the west and east coasts of Greece. b) brief information on the Mesohellenic Trough potential (25).



b)

	Location:	Mesohellenic Trough is located onshore in W Macedonia and W Thessalia - N Greece.
	Distance from Athens	300 km NW
	Area:	open acreage
	Logistic facilities:	Near Thessaloniki and Ioannina airport. E90 motorway.
	Available information: Wells: Legacy seismic lines: 2012 offshore lines: Total seismic lines:	 NP-1, NP-2, AG-1 (910 m), AG-2 (930m) 1,086 km - 1086 km
	Structural Environment:	Mesohellenic Basin is a half-graben along the suture zone of the Apulian and Pelagonian basement blocks.
	Stratigraphic setting:	Formations from bottom to top: Kranea Fm, Eptachori Fm, Pentalofos Fm and Tsotili Fm.

Other sources indicate maximum storage capacity in the Pentalofos formations between 1,435Mt and 5,000Mt of CO_2. Although this capacity is highly theoretical, it provides the measure of the potential CO_2 amount that can be stored and is equivalent to 396bcm of natural gas burnt, that is about 80% of the annual consumption of gas of the EU. However, more realistic estimations suggest 216Mt of CO_2 storage capacity in Pentalofos and Eptachori. This in turn represents emissions from around 60bcm consumed, or equivalent to 10 years of natural gas consumption in Greece.

From a procedural and legislative point of view, the environmental and spatial planning for the area will need to be enlarged and updated by introducing natural gas CO_2, specifications for storage of thermogenic gases, but also the exploration and exploitation of possible gas at the deeper layers of the Mesohellenic Trough.

A Strategic Environmental Impact Study must take in consideration the presence of thermogenic gases and the storage of CO_2 in the Regional Unit of Grevena. A first spatial study of influence to ecosystems and land use in the area was published by HHRM in June 2020.

Florina basin

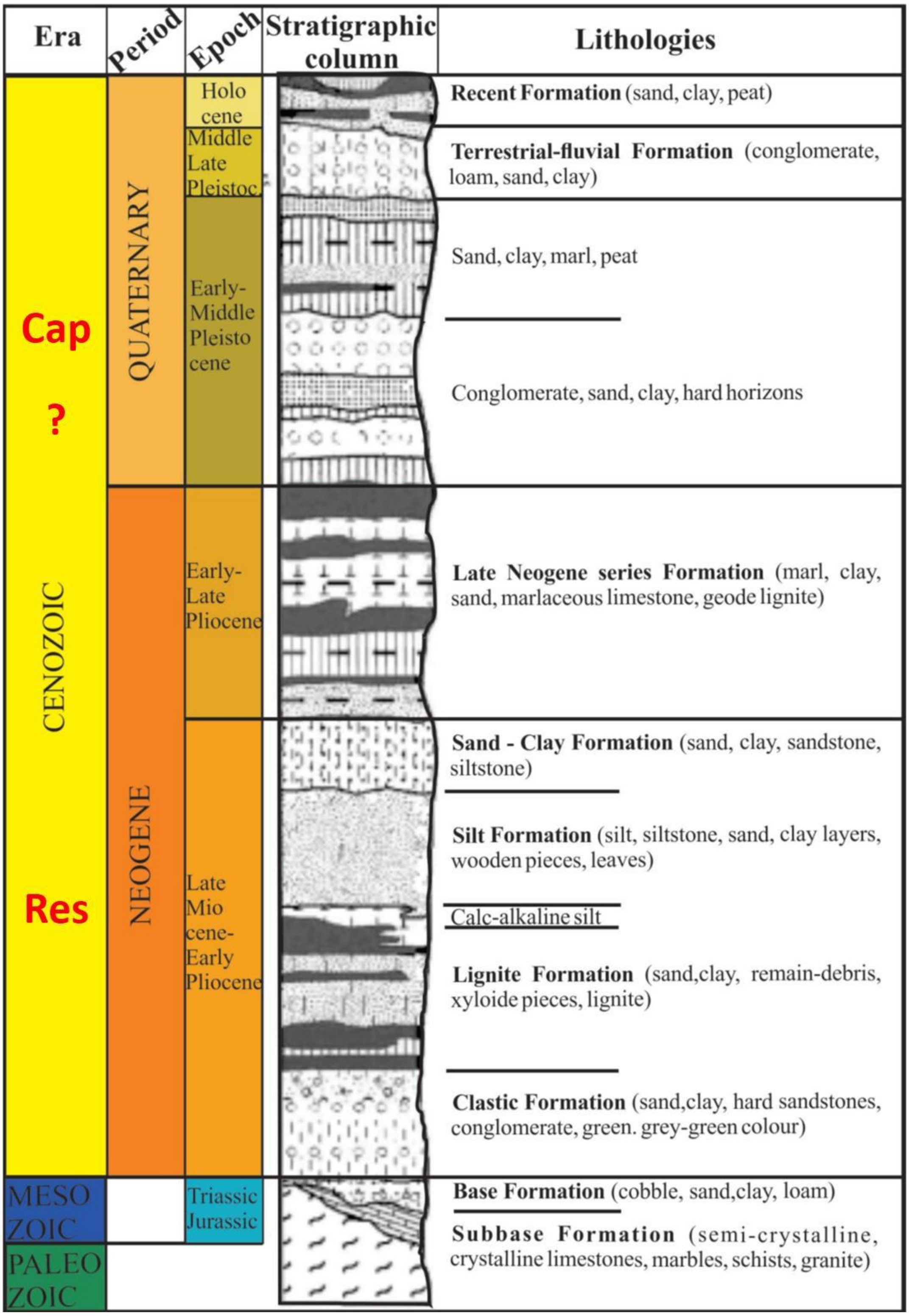
The Florina Basin is established since long time as an industrial site of commercial exploitation of CO_2 (industrial gas). The Florina basin holds large amounts of CO_2 dissolved in the aquifers, probably equivalent with about 50% of the total yearly emissions of CO_2 in Greece. The site can be used for the understanding of the limitations of the application of CCS technology in the region (15). The western side of the basin entails the Florina-Ptolemaida-Amyntaio axe with NNW-NSW direction and probably represents the end point from where escapes the CO_2 naturally enclosed in the subsurface. It should be noted that the Florina basin is a natural example of surface leakage of CO_2.

The CO_2 migration and escape could have taken place between 6.5-1.8Ma (26). The NE-SW directional faults, which were created before or during the formation of the basin, acted as escape paths for CO_2 (and continue to date) to the surface of the earth. Carbonate-rich springs and CO_2-rich gas vents may be the result of a slow gushing of magmatic, hydrothermal CO_2 gases along faults (27).

Table 9: Florina properties.

Florina
CO_2 storage space: The thickest reservoirs (1km) are located close to the basement in the wider area of Mesochori. The sedimentary environment of river crossed alluvial formations can favour the geological storage of CO_2 and the retention of CO_2 without escape pathways (Figure 9) (26). The CO_2 reservoir of the Florina Basin is located at a very shallow depth (approximately 300m).   **Cap-rock:** Neogene marls and clays cover most of the basin (136.4km^3). The Mesochori cap rock consists mainly of clay sediments. Surface escapes of CO_2 take place in areas where these Neogene sediments are absent.   **Storage capacity:** Unknown   **Depth of the formations:** 300m   **Porosities:** Unknown   **Structural setting:** Normal faults   **Seismicity:** Moderate   **3D model:** A 3D geological model was run in the shallow sandstones and conglomerates of Mesochori at 300m depth and helps to understand the migration process.   **Leakage mechanism:** The CO_2 in the Florina Basin migrates either through the pores of permeable geological formations, or when it is dissolved in water. The source of CO_2 is migration takes place under a few hundred meters of depth.

Figure 9: Lithostratigraphic column of the Florina-Ptolemaida-Amyntaio axe (26).



Central Macedonia

West Thessaloniki

The Thessaloniki basin, located west of the city of Thessaloniki, covers a vast land area of over 4,200km^2, along with an additional 4,000km^2 offshore. It was formed during the Lower Eocene and is primarily composed of clastic sediments like conglomerate, sand, and clay, with some limestone and marl deposits (Figure 10). The basin's basement consists of high-grade metamorphic rocks from the Axios zone. Notably, the basin contains thick sandstone layers exceeding 500m in thickness, making it a potential site for CO_2 storage. The sand/clay ratio in the aquifer varies from 40% to 90% and is influenced by brackish structures. Depths in the basin range from 900-2,400m, which is suitable for CO_2 storage.

Comparisons with the Epanomi gas field to the east of Thessaloniki reveal similar geological features. The Thessaloniki basin has the capacity to store CO_2 emissions from nearby industries, including a cement plant and a refinery plant. The existing Combined Cycle Gas Turbine Unit releases 1.9Mt of CO_2 annually. The basin's high temperatures at reservoir depths allow CO_2 to remain in a supercritical state, reducing the risk of leakage. However, low porosity (5%) and varying permeability levels (from a few mD to 120mD) limit its overall significance for CO_2 storage.

Figure 10: Geological section of the Thessaloniki basin (28).

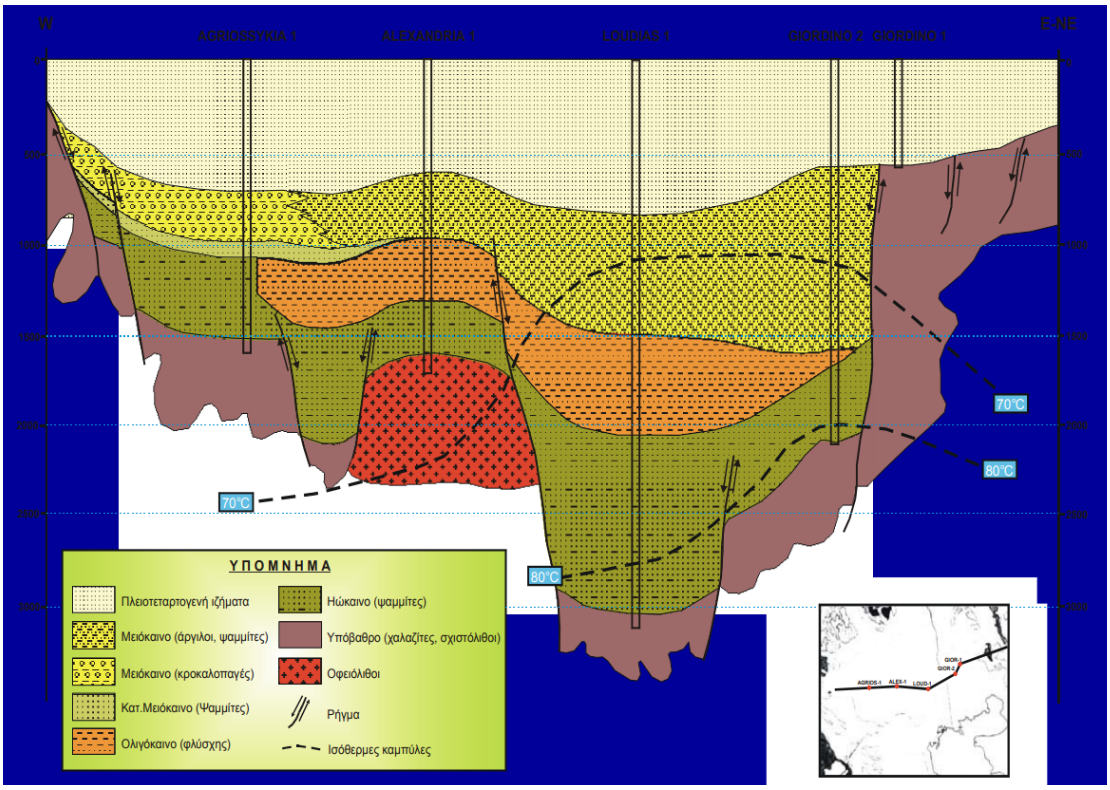


Table 10: West Thessaloniki basin properties for storage.

Summary	West Thessaloniki	Clayey part	Alexandria
CO_2 storage thickness (m)	100	21	180
Cap-rock thickness (m)	average 1,200	unknown	unknown
Storage capacity (Mt CO_2)	460	145	35
Storage capacity (RWE, 2006)	645Mt		
Storage space (km^2)	1,700		
Aquifer depth (m)	1,200-2200	2,400	900
Porosity (%)	5-20		
Permeability (mD)	very low to 120		
Structural setting	stable with limited faults		
Pore volume (km^3)	10.2	3.21	0.76
Hydrocarbons presence	no	no	no
Cap-rock quality	very good	very good	good

Injectivity	poor		
Measured temperatures	65-79		
Escape risk	low	low	unknown

Epanomi gas and CO_2 fields

The Epanomi gas field, discovered in 1988, produced 19 thousand cubic feet of gas per day and some light oil in a 1989 test. The field is situated on a paleo-erosional surface of Upper Jurassic-Lower Cretaceous age limestones with 1% average porosity. It is underlain by Oligocene flysch, Miocene clays, and conglomerates, all covered by Pliocene-Quaternary sedimentary layers.

The estimated gas reserves in the Epanomi field are about 500 million m^3 of natural gas, comprising 71.8% hydrocarbon gases and 26.6% non-hydrocarbon gases, including 22.6% CO_2 (29). The hydrocarbon gases are of catagenetic origin and considered wet gases, potentially originating from mixed sources.

In the EP-B1 well east of Epanomi, the gas is mainly CO_2 (93.5%) and comes from the evolution of Mesozoic dolomitic limestones. This inorganic origin suggests that the primary source rock products in the area are hydrocarbons, with potential capacity for storing 2 million metric tons of CO_2 in Upper Jurassic-Lower Cretaceous limestones at depths of 2,600m (30).

Table 11: Epanomi gas and CO_2 field properties for storage.

Summary	Epanomi
CO_2 storage thickness (m)	250
Cap-rock thickness (m)	1,600
Storage capacity (Mt CO_2)	2
Storage space (km^2)	unknown
Aquifer depth (m)	2,000 at 80°C

Porosity (%)	tight Jurassic limestones 1%
Permeability (mD)	?
Structural setting	Paleo-erosional
Pore volume (km^3)	?
Hydrocarbons presence	yes
Cap-rock quality	good
Injectivity	very low
Measured temperatures	80°C at 2,000m
Leakage risk	unknown

Eastern Macedonia

The Prinos Basin

The Prinos Basin is an active oil field with a neighbouring depleted natural gas field named South Kavala. An underlying aquifer characterises the entire site creating the ideal conditions for a geological storage complex of CO_2. The advantage of depleted or semi-depleted hydrocarbon reservoirs, is that they provide several geological, geophysical, drilling and production data.

Although, saltwater deep aquifers typically do not provide sufficient data to evaluate the CO_2 storage potential, in the case of Prinos Basin, the aquifer is situated very close below the reservoir. The combination of production of the remaining Prinos reservoir(s) using Enhance Oil Recovery (EOR) technics to be extracted, and the CO_2 storage process make the Prinos Basin an ideal case site.

This sedimentary basin is a rift basin situated in the North Aegean Sea. Its surface extends 800km^2 (Figure 11). It was formed by normal faults trending NE–SW at the southern end of the massif of the Rhodope mass, between the islands of Thassos-Thassopoula and the mainland. The Prinos oil field was discovered in late 1973 at sea level depths of about 30m and covers an area of about 4.5km^2 in the Gulf of Kavala. The reservoir is located at a depth of about 2,500m below sea level and extends up to

2,850m depth (31). The porosity is around 18% and the reservoir volume is around 30km[3] (32). The depth of the saline aquifer varies from 1 to 3.5km from the surface and extends in an area of about 800km[2].

Figure 11: Map showing the Prinos-Kavala sedimentary basin and the oil and gas reservoirs in the region (31).

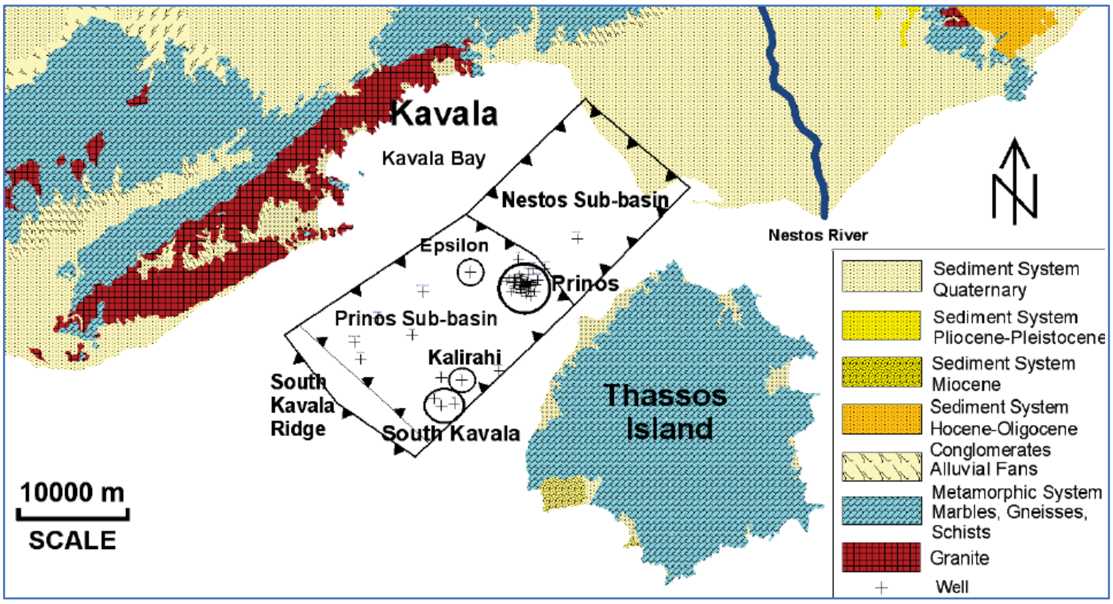


Table 12: Prinos oil field and South Kavala gas field properties for storage.

Prinos and South Kavala
CO_2 storage space: The turbiditic sediments of Prinos are the reservoirs which produce oil between the first and third evaporitic horizons. These sediments may serve today for CO_2 storage or completion of EOR. In South Kavala, the gas reservoirs between the fourth and fifth evaporitic horizons may serve for gas or CO_2 storage. Their thickness exceeds 1km. **Saline layers:** The evaporitic sediments (s.l.) are of Messinian age and divided in seven evaporitic layers alternating with clastics, anhydride and dolomite (33) (34) (35). These sediments have an average thickness of 800m. **Cap-rock:** The cap-rock consist of saline domes and evaporative sediments, overlying sandstones and non-consolidated sediments, with a total thickness of up to 2.3km (36) (37). The post-evaporitic series of Pliocene-Pleistocene age cover the

entire watershed and ensure the impermeability of the underlying reservoirs of gas or oil. More specifically, the cover in the Prinos reservoir for each of the three layers of the oil reservoir is a clay layer 10-14m thick which has been deposited under the evaporitic layers and seals the reservoir far below the top cap rock (31).

Depth of the formations: The depth from surface to top of the oil reservoir (1-3.5km) is considered sufficient to maintain CO_2 in its supercritical state and this is a favourable feature of reservoirs for CO_2 storage, in combination with EOR under full mixing conditions.

Porosities: around 18%

Structural setting: Anticline faults work as structural traps for CO_2.

Seismicity: It is significantly low and does not present a potential risk for the CO_2 storage implementation.

Leakage: Given that the Prinos reservoir undergoes depletion evaporites seem to ensure the impermeability of the reservoir. To date no hydrocarbon escapes have been observed such as e.g., from fault activation by possible seismicity of the area (34). On the contrary, in the reservoir of South Kavala upward movements of hydrocarbons were observed due to the activation of a fault (34). The boreholes are old and possible non-compliance with environmental regulations could appear or the retention of CO_2 in the underlying aquifer may be problematic.

EOR combined process: In the case of combination of CO_2 storage with EOR, could maintain oil production in conjunction with the CO_2 injection periods. Further, in the shallower depths of the reservoir, a CO_2 zone of increasing size can be formed above the oil zone. With continued oil production, a larger volume of the depleted reservoir voids can be occupied by the injected CO_2 improving the storage capacity of CO_2. The use of saline aquifer formation is an alternative or additional process. With a porosity of around 18% at 2.4km below sea level, Prinos can present a potential storage capacity of 1,221 or 1,350Mt CO_2 (16) (38) (39). According to simulations, the CO_2 emissions from neighbouring power plants can be stored in the saline aquifers of Prinos for about 52.6 years. The number of existing boreholes (68 boreholes) penetrating the reservoirs in Prinos and reaching the aquifer is important and can favour the fast injection of CO_2 reduce time and costs.

Table 13: Summary data for storage in Prinos.

Summary	**Prinos**
CO_2 storage thickness (m)	1,000
Cap-rock thickness (m)	1,800 up to 2,300
Storage capacity (Mt CO_2)	19
Basin storage capacity (Mt CO_2)	1,350
Storage space (km^2)	4,500
Storage depth (m)	2,500-2,850
Aquifer thickness	800
Aquifer depth (m)	1,000-3,500
Aquifer surface (km^2)	800
Porosity (%)	18
Permeability (mD)	50
Structural setting	anticline fault traps
Pore volume (m^3)	30,000
Hydrocarbons presence	producing depleted
Cap-rock quality	very good
Injectivity	3 confining zones
Measured T/P	122°C at 1,377m depth
Leakage risk	very low
Seismicity	very low

Table 14: Summary data for storage in South Kavala.

Summary	South Kavala
CO_2 storage thickness (m)	unknown
Cap-rock thickness (m)	unknown
Storage capacity (Mt CO_2)	16
Basin storage capacity (Mt CO_2)	1,240
Storage space (km^2)	5
Storage depth (m)	1,620-1,730
Aquifer thickness	
Aquifer depth (m)	1,000-3,500
Aquifer surface (km^2)	unknown
Porosity (%)	18
Permeability (mD)	50
Structural setting	anticline fault traps
Pore volume (m^3)	unknown
Hydrocarbons presence	producing/depleted
Cap rock quality	very good
Injectivity	2 confining zones
Measured T/P	80°C/150 bars
Leakage risk	low
Seismicity	low

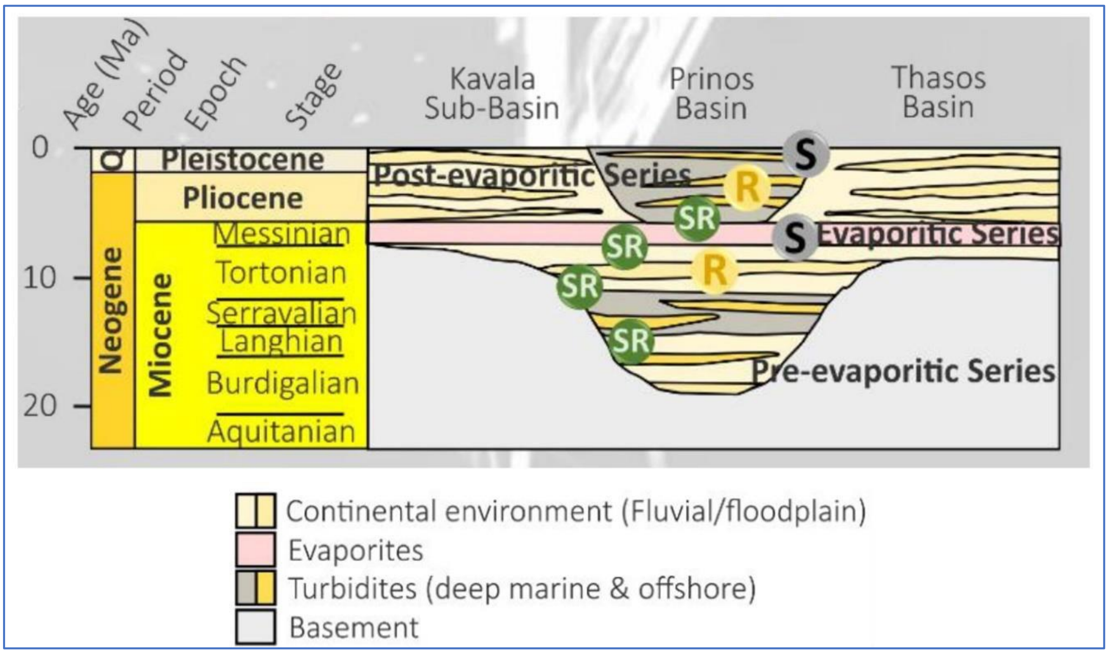
South Kavala: An eye on the CO_2 storage alternative to the underground gas storage project

The development of an Underground Natural Gas Storage (GUS) in the depleted field of South Kavala has been the subject of special studies in the past. In 2000-2001 SHELL prepared (commissioned by DEPA) a relevant technical study which demonstrated that the site is suitable for the development of such a scale project.

The gas reservoir of South Kavala is depleted but covers an area of 5km^2 in the Gulf of Kavala (Figure 11). The sea depth in the area is about 51m. The reservoir is turbidite sandstone, located at a depth of between 1,620m and 1,730m, with an impermeable evaporite cover (Figure 12) (35).

The structural and lithostratigraphic settings do not show significant differences from those of Prinos (pre-evaporitic series, evaporitic series and post-evaporitic series). The structure of the gas trap is like that of the structures of Prinos, a lattice of an anticline fault traps and a sedimentary decoupling. The reservoir is located between the fourth and fifth evaporative horizons with the former forming its watertight cover (35).

Figure 12: Geological section of the Prinos basin with possible CO_2 storage at various depths. R=Reservoir, S=Seal/Cap-rock (25).



Review of selected sites

Capacities of CO_2 storage and distances from industrial facilities

Table 15: Country's capacity of CO_2 storage (data from figure 6).

Acceptability criteria	MESSOHELLENIC TROUGH	WEST THESSALONIKI	EPANOMI	SOUTH KAVALA	PRINOS
Storage resource (Mt)	216-1,435	640	2	35	
Injectivity	Good 15% porosity	Low porosity Low permeability	Low porosity to tight	Average to Good 15 % porosity	
Integrity	2 confining zones at depth	1,200	1,600	2,500-2,850	1,600-1,730
Depth	2,500	900-2,400	2,600	1,600	1,600

Table 16: Distances from major port facilities and industrial plants (data from figures. 17,18, 19).

Distance from port facilities (km)			**Distance from industrial facilities (km)**		
Grevena	Alexandroupolis	415	**Grevena**	Komotini power station	365
	Kavala	280		Prinos	300
	Volos	165		Volos National Gas Grid	165
	Thessaloniki	145		TAP close to Ptolemaida	65
	Igoumenitsa	125		Ptolemaida	60
				IGI close to Kozani	40
Thessaloniki	Igoumenitsa	275	**Thessaloniki**	Komotini power station	225
	Alexandroupolis	270		Volos National Gas Grid	180
	Volos	180		Prinos	160
	Kavala	135		Ptolemaida	130
				TAP close to Nea Magnisia	20
				IGI close to Nea Magnisia	20
Epanomi	Igoumenitsa	310	**Epanomi**	Komotini power station	250
	Alexandroupolis	295		Prinos	220
	Volos	220		TAP close to Nea Magnisia	180
	Kavala	160		IGI close to Nea Magnisia	165
				Ptolemaida	55
				Volos National Gas Grid	55

Figure 13: Distance of Grevena from port facilities and industrial plants.

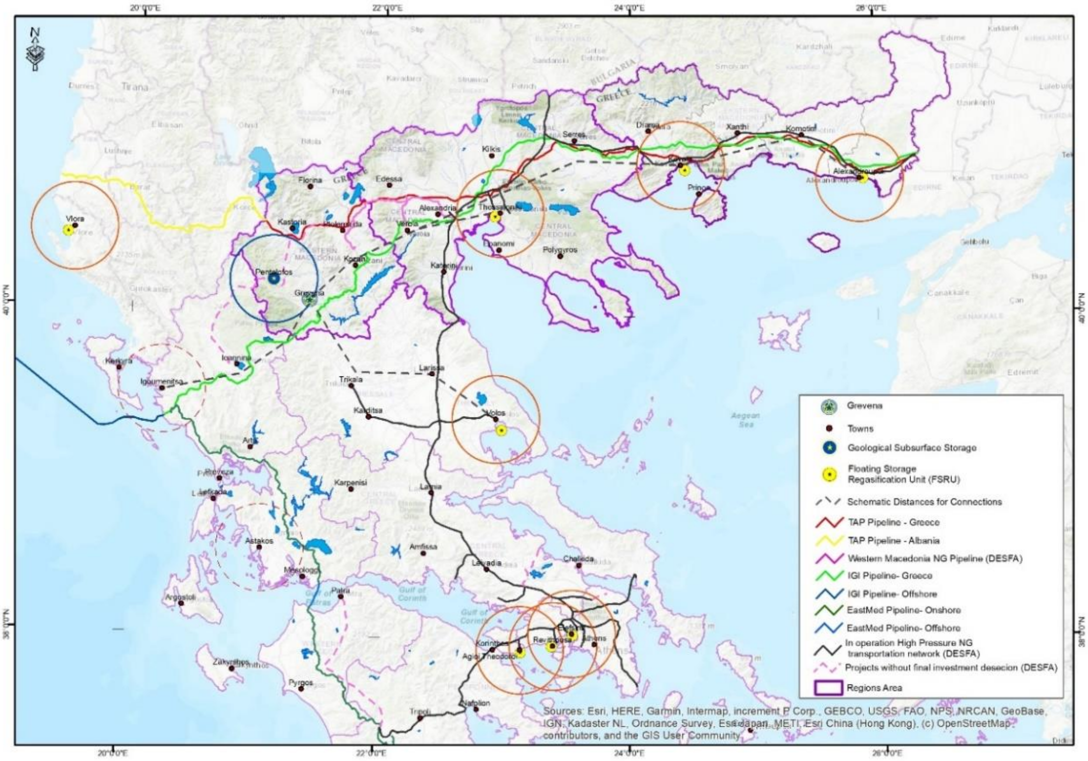


Figure 14: Distance of Thessaloniki from port facilities and industrial plants.

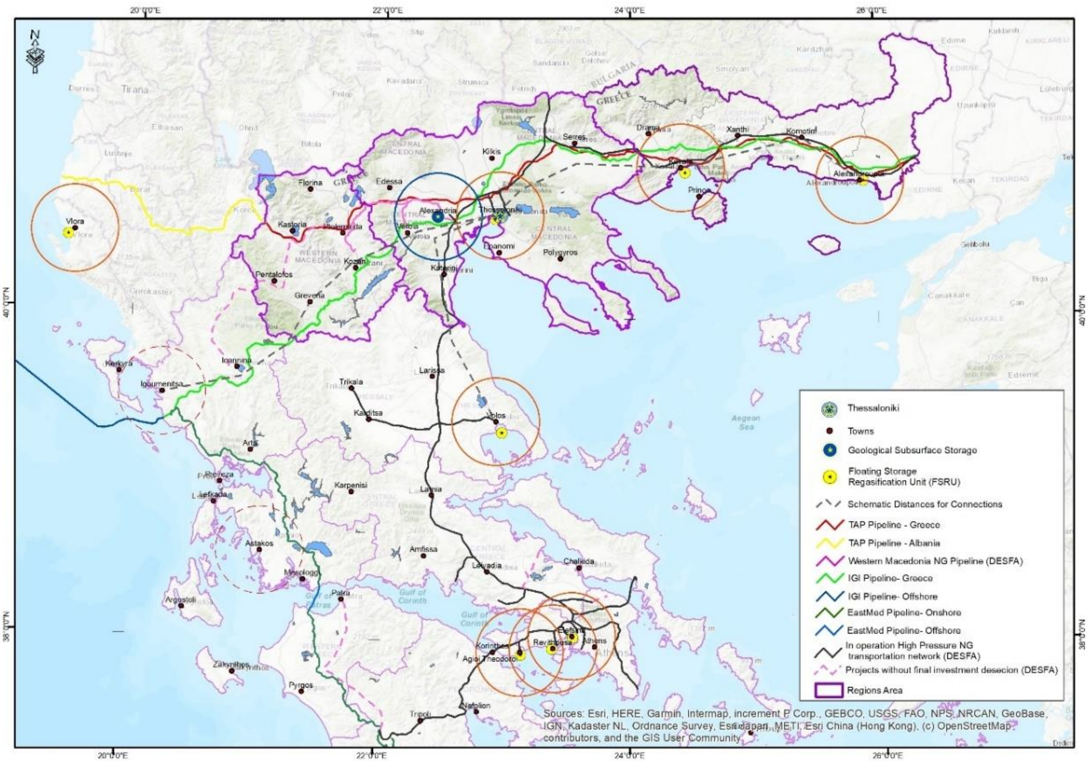
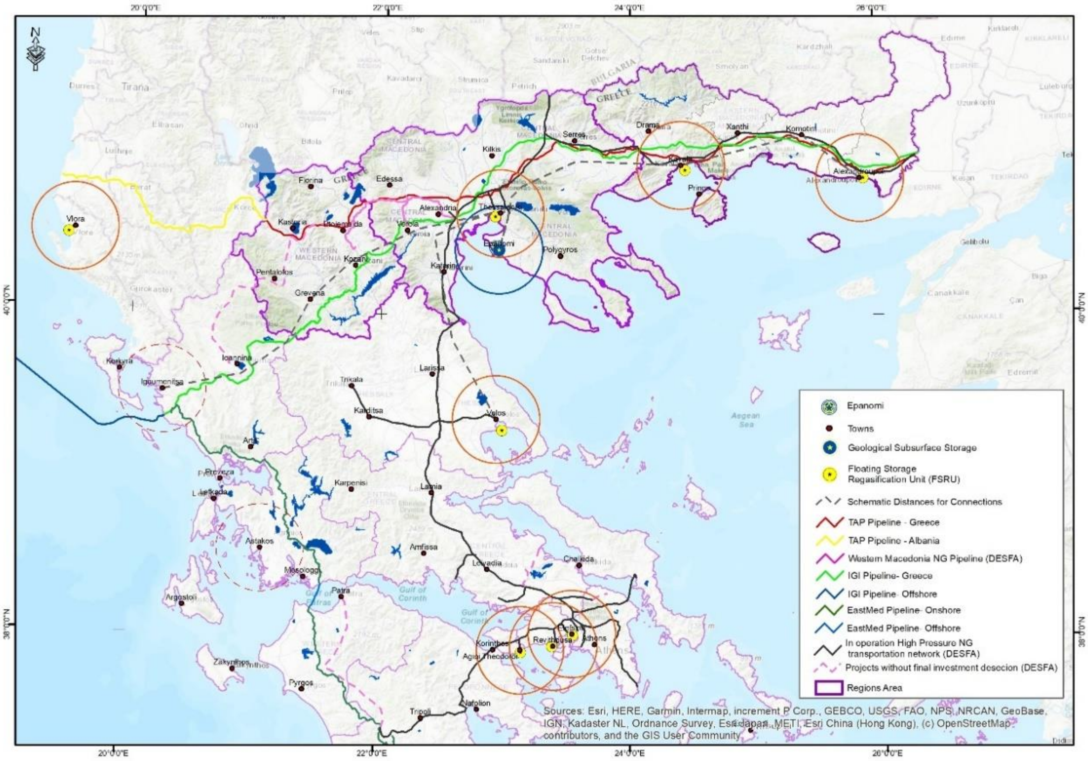


Figure 15: Distance of Epanomi from port facilities and industrial plants.



Economics of transformation of oil and gas fields to storage sites

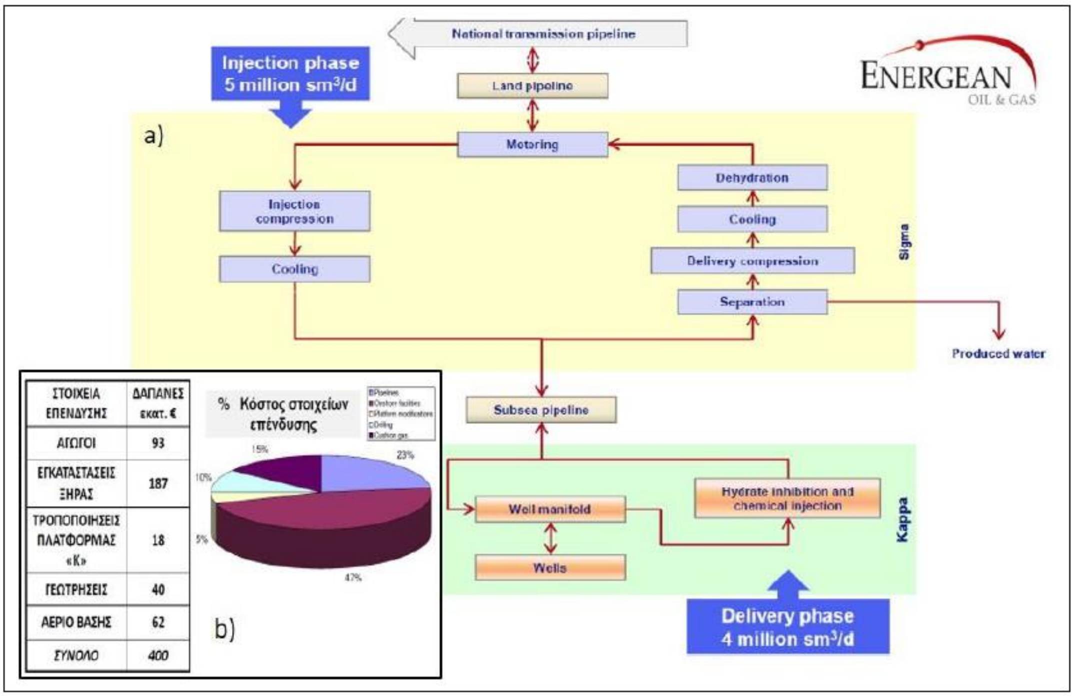
<u>CO_2 storage in South Kavala, an alternative for gas storage?</u>

The daily gas storage capacity in South Kavala was estimated at 4.0 to 5.0 million m^3 while the annual volume of gas stored could be around 360 million m^3 in two cycles of storage per year. The total investment cost in 2010 was estimated at €400MM with an error margin of 40% (Figure 16). However, later estimates, taking account of the substantial increase of gas prices, put the estimate at around €800MM. Sometimes old economics, before the pandemic and the Russia-Ukraine war, appear more pragmatic.

It is worth noting that this project has been included in the Business Development Plan of HRADF (Hellenic Republic Asset Development Fund). This infrastructure was considered as a solution to enhance the energy security of the Greek gas market (security of supply). A tender organised by HRADF in April 2023 to attract an investor, proved unsuccessful once again.

Given Greece's extensive gas network and major gas interconnections with neighbouring countries the need for a permanent underground gas storage facility is considered necessary. It should be noted that Greece is the only country in the EU that lacks permanent gas storage facilities.

Figure 16: Cost analysis of CO_2 storage in South Kavala, published by Energean (Technip/Genesis-Energean Oil and Gas, 2010).



Compared with facilities providing regasification in neighbouring locations of eastern Macedonia, a storage facility of the size of South Kavala depleted reservoir could deliver and store natural gas only twice a year. The number of planned FSRU facilities in the eastern coasts of Greece renders this project of gas storage probably not that competitive since 40% or 50% of one bcm can be delivered by 3 to 6 LNG carriers of 145 to 174 thousand cubic meters of liquefied gas each on a very fast delivery schedule. In this framework, the technical requirements and economics of the transformation of the depleted gas reservoir in CO_2 storage should be examined.

Saline aquifers of Prinos

The cost of drilling for storage of CO_2 in the saline aquifer of Prinos was estimated some years ago at €11.6MM out of a total capital investment of €38.4MM, while other operating yearly expenses would be around at €3MM. Other previous studies estimated a theoretical CO_2 storage capacity of Prinos at 19Mt CO_2, equivalent to only 9 months of CO_2 emissions from the power plants of Macedonia (Amyntaio, Ptolemaida, Meliti, Ag. Dimitrios, Kardia, Meliti, Komotini) (18). These estimations, in the light of the de-lignitisation course renders the economics questionable. Only the injection of CO_2, combined with enhanced oil recovery technics to maintain oil production can balance the cost.

Economics for storage in non-oil and gas sites

The lignite and gas plants are remote from future CCS or CCUS facilities and the nearest site to transfer CO_2 for subsurface storage is the Mesohellenic Trough. Although a comeback to the use of lignite took place in 2022, due to the cumulative economic impact of the pandemic and the war in Ukraine, the government policy remains in place to shortly abandon the use of lignite. Before 2020 PPC's eight (8) lignite power plants were producing 56% of the electricity of the country. This is not the case today. Provided that the power plants will continue to function with a mix of lignite and natural gas for at least two decades, the area can become suitable to store CO_2.

Cost of CO_2 storage and long-term investment

Carbon dioxide is a derivative of the combustion of lignite or natural gas to produce electricity. The annual carbon dioxide release in Greece was 115Mt in 2007 while in 2020 it was 60Mt, almost the half. In 2019 the industry released 40.4Mt, 26Mt from lignite for electricity, 5.4Mt from hydrocarbons, 5.3Mt from cement factories, 2.1Mt from metallurgy and 1.6Mt from others uses. Many of these industries do not need to store all emitted CO_2 because they convert part of it into other polymers and products with higher economic value (e.g. plastics, concrete, biofuels) while at the same time reducing the carbon tax.

The benefits from a carbon storage project in Northern Greece can contribute to the reduction of emissions even if lignite will be replaced progressively by gas. A direct advantage is the reduction of the cost of carbon tax for the industry (around €100/ton these days). For instance, 40Mt of CO_2 emissions from industrial activities would account for €4BN in the financial statements of the companies, while at the same time would reduce the intermediate income of the country's budget.

It is necessary though to consider various investment scenarios from 10 to 40 years, to determine the investment costs, operating costs, and net present value (NPV) created for the country's economy. One of the more critical factors in the entire project will be the choice of transportation methods and the paths, land or maritime, of the compressed CO_2.

The cost of CO_2 storage after studies, seismic and drilling, according to IEAGHG (40) varies around €14.3/ton. This is spread out as follows:

- Injection, €3
- Pre-feed, €6
- Operating cost, €2.5
- Close-down, €1

The estimated 60Mt of emissions in 2022 in Greece would represent, at 100%, 60 times €14.3MM, or €858MM while the tax on carbon would represent a total cost of €6BN. The difference is a multiple of 7, provided that the selected sites can do the job after 2 to 5 years of preparation and a time window of 10 to 40 years of follow up after the "close down".

When comparing CO_2 transport scenarios, it would be necessary to take into account different investment periods of e.g. 10 or 40 years, in order to first determine the relative NPV of operating and investment costs. This would then allow to draw conclusions about the possible ways of transfer of CO_2 to determine which would be the most advantageous method of transport.

Cost of storage versus emitted volumes of CO_2

From an economic point of view, with the embargo on Russian natural gas and the increase of LNG imports, the lack of underground storage facilities in Greece does not comply with the recent EU strategy. The exploitation of the lignite in Western Macedonia, the potential gas reserves in the Mesohellenic Trough and the Epanomi field, as well as the continuation of oil production in Prinos and neighbouring fields hold a special place for the storage of carbon dioxide, which is a derivative of the combustion of lignite or natural gas to produce electricity. Carbon capture, utilisation, and storage technologies such as CCUS from combustion but also DACS directly from the atmosphere can also contribute to the capture of the emitted CO_2. The annual carbon dioxide release in Greece amounts to 60Mt in 2020 while in 2007 it was about 115Mt, mainly due to a decrease in lignite-produced electricity and the contraction of industrial activity. This significant decrease demands attention to the economics which must conform with the long-term prerequisites for these projects, from 10 to 40 years.

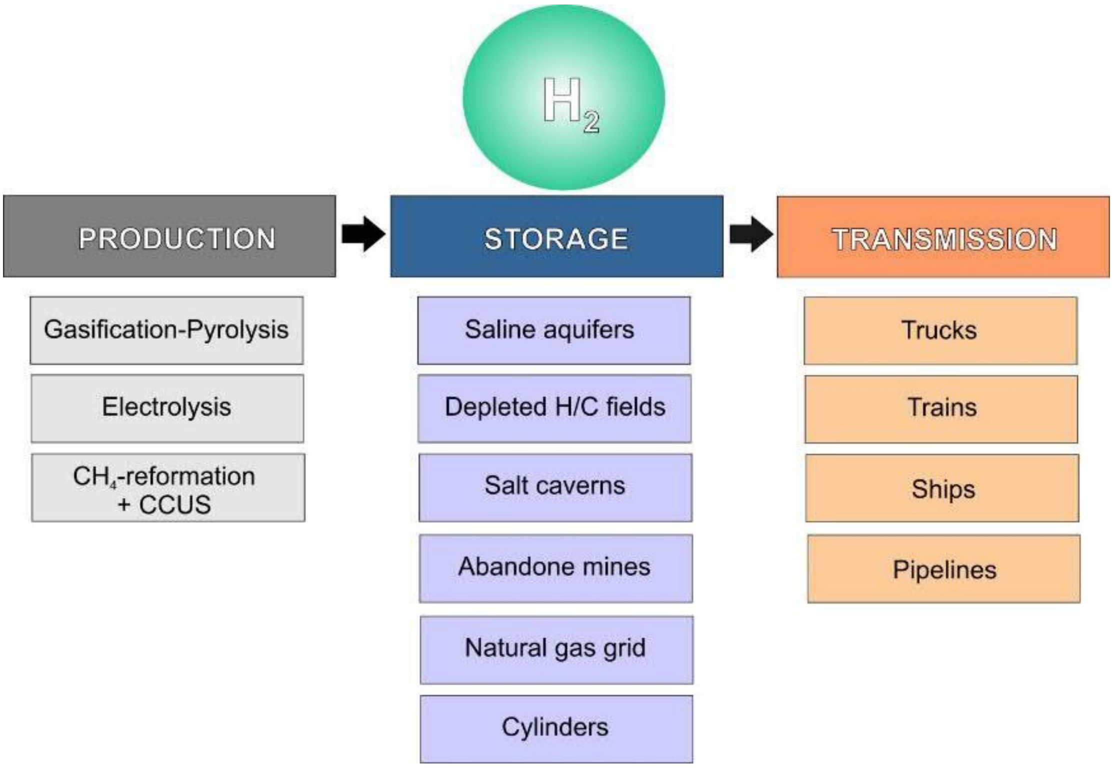
Chapter 4: Prospects for combined use of Hydrogen and CCUS technologies in Greece

Greece has significant prospects for the implementation of CCUS technologies, given the relatively high level of CO_2 emissions, its substantial industrial activity and the technology options currently available or in the process of development (e.g. building of CO_2 carrying vessels). In addition, there is considerable underground storage potential to be found in the region of Western Macedonia and particularly in the Pentalofos and Eptahori formations of the Mesohellenic Trough and the broader Prinos area.

The generated CO_2 from the Ptolemaida V power plant, which will be the only active power plant after 2028 in Greece, will be able, along with industrial emissions, to provide CO_2 to the above storage sites. Potential synergies between CCUS and the hydrogen value chain may result in major benefits for achieving a sustainable circular economy along with the reduction of atmospheric CO_2 emissions.

The hydrogen value chain includes the stages of hydrogen generation, storage, transmission to storage and distribution to final uses (Figure 17) (41). Hydrogen conversion into a usable form for end-users is regarded by some researchers as part of the value chain (42). CO_2 is emitted as a byproduct of the energy production process, whereas hydrogen is a primary product that has to be generated.

Figure 17: Schematic diagram of the hydrocarbon value chain.



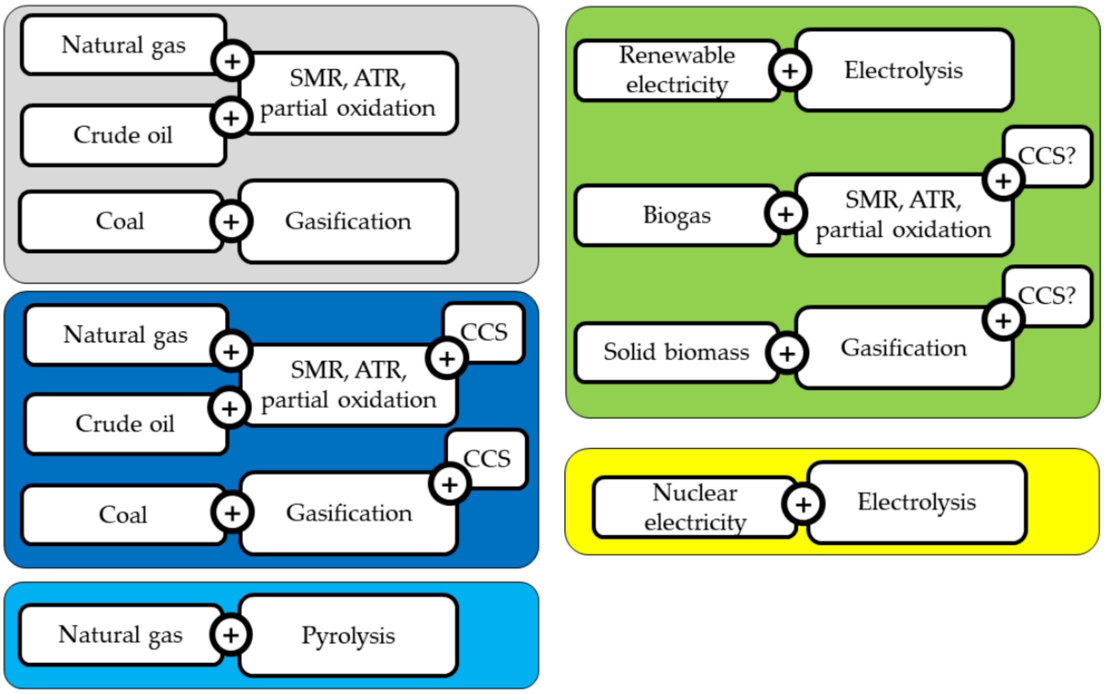
Hydrogen production methods are codified by different colours depending on the source that is used for the generation (Figure 18).

- Grey hydrogen is generated by hydrocarbons; a process that leads to significant CO_2 emissions. Steam reforming is the most common grey hydrogen generation method, which employs thermal energy as steam to decompose natural gas into hydrogen and CO_2. Afterwards, the produced hydrogen is separated from CO_2 usually through membranes (43) (44).
- Blue hydrogen generation is also based on hydrocarbons, combining CCUS technologies to reduce the emitted greenhouse gases. Blue hydrogen is considered as a viable solution to diminish CO_2 emissions from the hydrogen generation process. Fossil fuel pyrolysis leads to the production of turquoise hydrogen (41) (45).
- Green hydrogen has gained increased attention over the last years, since it is produced via a carbon-neutral method enabling the development of zero-carbon energy independence. This type of hydrogen is generated by

electrolysing water to decompose it into oxygen and hydrogen gas, using renewable electricity or bioenergy. Various technologies are available for green hydrogen generation, such as Proton Exchange Membrane (PEM) method, alkaline electrolysis and solid oxide electrolysis. The main deterrents to large-scale green hydrogen production are the increased water consumption that is required to produce large amounts of hydrogen via electrolysis and the irregularity of renewable energy supply (41) (46) (47).

- Another hydrogen type is the yellow or purple hydrogen, which is also produced via electrolysis, using nuclear energy instead of renewable (41) (45).

Figure 18: Hydrogen generation methods, SMR=Steam Machin Reforming, ATR=Autothermal Reforming, CCS=Carbon Storage and Sequestration (41).



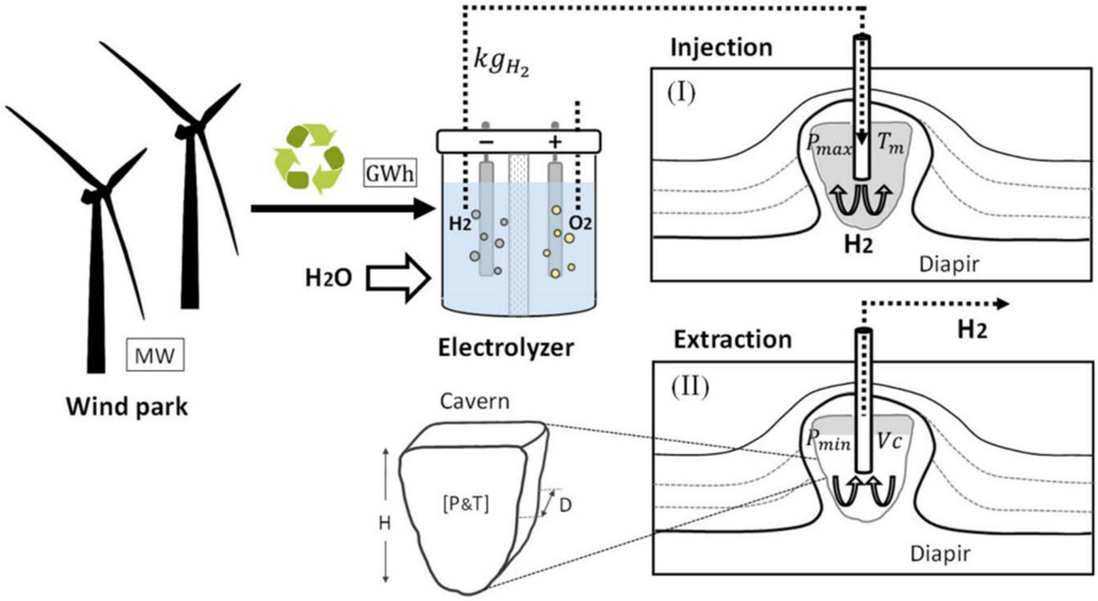
Hydrogen storage and transportation could benefit from the accumulated experience in the natural gas storage and transport sectors, since they share several common properties. Hydrogen storage can significantly contribute to the energy sector and the decarbonisation plan ensuring the energy adequacy in times of deficiency. The stored hydrogen can be converted to useable energy forms to fulfil higher energy demands. Underground hydrogen storage (UHS) can be performed in natural or artificial storage sites, including porous lithological formations, such as saline aquifers and depleted hydrocarbon fields, abandoned rock mines and salt formations that can be converted into salt caverns (48) (49) (50) (51). Aboveground hydrogen storage is also feasible using the Power-to-Gas (P2G) method that can store mixtures of hydrogen with natural gas by utilising the natural gas network (51).

Saline aquifers have been used as storage sites to accommodate natural gas for several years. The necessary combination of a permeable aquifer with impermeable adjacent rocks for mitigation of potential leakage phenomena may be identified in various areas and exploited for UHS. Storing hydrogen in the pore system of saline aquifers requires the displacement of the pore-water, which is restored when the gas is withdrawn from the reservoir.

Depleted oil and gas fields are among the most promising alternatives for hydrogen storage. Having retained the hydrocarbons in geological time, (i.e. for million years) they exhibit the required quality characteristics for UHS. Another benefit from the use of depleted fields as hydrogen reservoirs is associated with the existing infrastructure that can be retrofitted and used for hydrogen storage and extraction. Any residual gas in the depleted fields can serve as required cushion gas for sufficient capture of the stored hydrogen.

Similarly, abandoned mines and existing rock caverns can be beneficial to UHS due to the existing facilities that can be utilised. Exploitation of salt caverns for hydrogen storage is widely adopted, due to the advantageous characteristics of salt deposits, including large capacity and adequate tightness (Figure 19). Excavating a salt cavern is more cost-effective than excavation of an underground rock mine. The only requirement is a well installation through which the salt formation can be dissolved to create the cavern and then hydrogen can be injected and retrieved from the cavern.

Figure 19: Green hydrogen generation, injection and withdrawal from a salt cavern reservoir (52).



Hydrogen can be stored at the aforementioned sites in various forms, such as gaseous phase, liquid phase, or chemically bound (41) (50). The hydrogen value chain involves the transportation of hydrogen in two distinct stages, the initial transmission from the generation facility to the storage site, where it is stored until it is required for utilisation and the final distribution from the storage site to end users. The produced hydrogen can be transported to the storage facility via pipelines, railway or shipping. Hydrogen pipelines are considered to be the most inexpensive option for gas transportation and can connect several countries serving many relevant facilities.

The expansion of the European gas and hydrogen pipeline networks will benefit Greece since hydrogen pipelines will most likely be constructed in the northern part of the country and the existing natural gas network will be extended. At the same time, DESFA has submitted a PCI proposal for the development of a dedicated hydrogen pipeline from Elefsina up to the Greek-Bulgarian borders, in line with the European Hydrogen Backbone initiative (Figure 20).

Figure 20: Potential expansion of the natural gas and hydrogen pipeline networks in Greece.

Mixing hydrogen in natural gas pipelines is known as gas blending and enables the potential of utilising existing natural gas networks. These networks are able to safely accommodate 10% of hydrogen in the mixture with the potential to reach up to 20% in local distribution systems (53) (54) (55).

Studies for the potential hydrogen blending in natural gas have also been conducted for end use systems and conclude that up to 25-30% of hydrogen can be injected into natural gas without provoking issues (54) (56) (57). Another suggestion is the conversion of the existing natural gas pipelines into hydrogen pipelines in order to diminish the required expenses for the development of a hydrogen pipeline network (Figure 21).

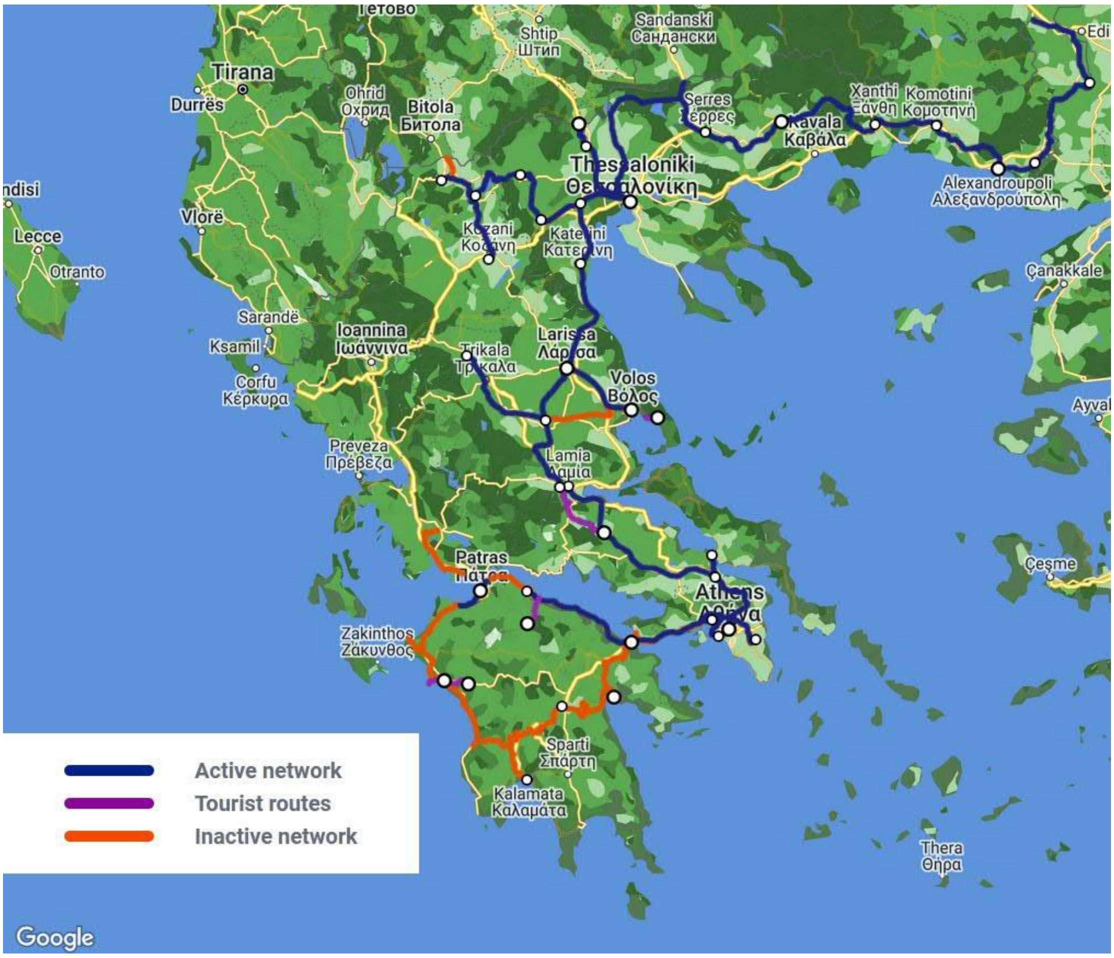
Figure 21: Existing pipeline network for gas transmission in Greece (National Natural Gas System Operator (DESDA) S.A., 2021).

Specific adaptation processes are necessary to retrofit the existing pipeline network to prevent potential leakage due to hydrogen properties, such as corrosivity. Expansion of the existing pipelines is needed because hydrogen has a lower density than natural gas (41).

Existing railway networks (Figure 22) could be utilised for hydrogen transport, as it has been already proposed for CO_2 (58). Shipping transportation is another versatile option, since it can serve multiple facilities in different countries and it is not constrained on specific routes. Ships that transfer hydrogen must comply with specific standards to ensure safe transport.

Hydrogen transferred via shipping shall be condensed to the highest permissible degree to facilitate the transportation and reduce the overall expenses. Hydrogen transportation in its gaseous phase by ship is not widely implemented due to space restrictions. Other hydrogen forms that are considered are ammonia, liquid hydrogen and LOHC (Liquid Organic Hydrogen Carriers). Hydrogen distribution to final users is feasible through pipelines or trucks, in compressed gaseous or liquid form. A multiple-criteria analysis focused on the distance, required density for the refuelling stations and volume is required to determine the appropriate method for every case (58).

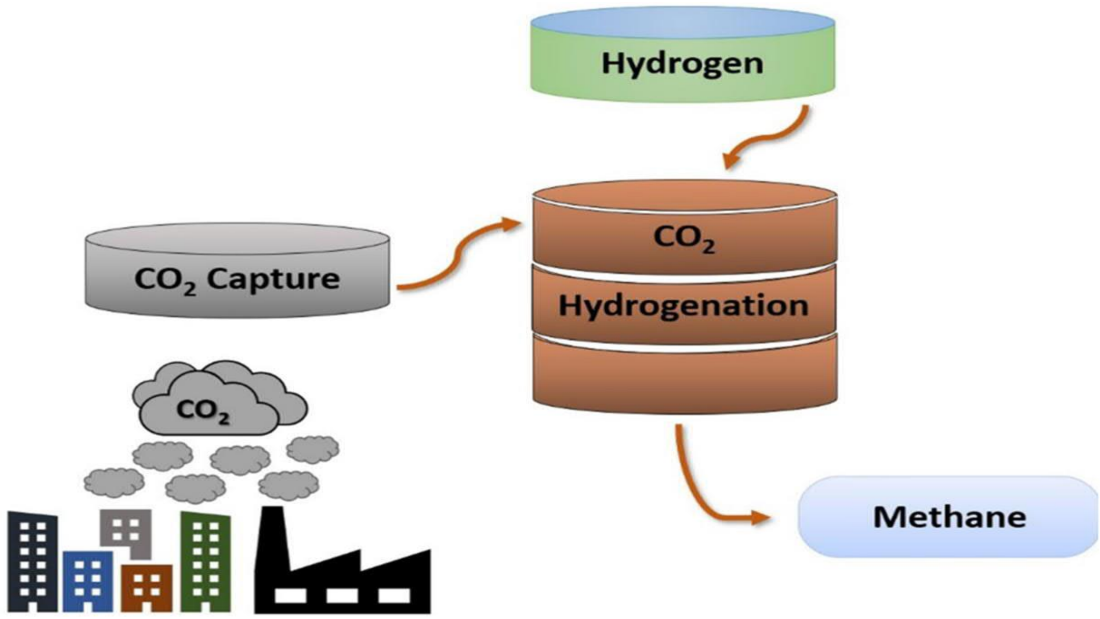
Figure 22: Existing railway network for gas transportation in Greece (Hellenic Railways Organisation (OSE), 2023).



Experience and knowledge gained over recent years and technological advances achieved so far have allowed the combined use of CO_2 and hydrogen in order to achieve optimal results. Scenarios of potential combined use of CCUS and hydrogen technologies are, as follows:

- Underground Hydrogen Storage (UHS) using CO_2 as cushion gas. The successful implementation of UHS requires an unexploited amount of gas to be stored within the reservoir, called cushion gas. The presence of this gas is crucial to maintain the required pressure levels in the storage site during hydrogen withdrawal, which is expected to be frequent and at high rates as determined by the energy requirements of the market (59).
- CO_2 hydrogeneration (or methanation) is a method that combines captured and stored CO_2 with hydrogen. The combination of CO_2 and hydrogen forms methane and water. Methane is used as an energy carrier due to its high density and enables safe storage and transportation. The implementation of CO_2 hydrogeneration for methane production does not emit carbon, provided that the required hydrogen is produced through a zero-carbon method, whereas methane can be used as fuel or converted into electrical energy (Figure 23).

Figure 23: Schematic representation of the CO_2 hydrogeneration process.



The proposed combinations could be implemented in Greece, focusing on the ports of Agioi Theodoroi, Elefsina, Thessaloniki and Alexandroupolis. Potential sites for geological gas storage in Greece are mainly located in the northern parts of the country and specifically in the Mesohellenic Trough, the Western Thessaloniki basin, the Prinos basin, as well as in the aquifer of the Ptolemais-Kozani basin (24) (60) (61) (62).

Chapter 5: CCUS implementation in Greece

Proposed CCUS hub networks

A key factor in achieving climate neutrality is the geological storage of CO_2 both nationally and globally. Based on data from the Global CCS Institute, out of 27 CCS facilities worldwide, 2,705 new facilities will need to be installed by 2050, bringing the total to 2,732 (5). Although in Greece, application of CCUS technology has been announced for the depleted hydrocarbon deposits of Prinos basin, there is very little information as to the industries, apart from power generation, which are likely to use this facility. The concept of a CCUS hub in Greece has yet not been examined in any detail. Most CCUS hubs are located close to industrial clusters worldwide, such as in Net Zero Teesside and Rotterdam, where emission sources are close together. The hub concept makes the CCUS technology an option for decarbonisation for emitters without requiring them to construct lengthy pipelines, drill storage wells, or assume long-term liability for the stored CO_2 (Figure 24).

So far in Greece a lot of attention has been placed on CCUS applications for power generation and less so for industry. In this study, we have already covered to some extent, the potential applications for power generation and therefore no further discussion is necessary at this stage.

In view of the fact that potential underground storage facilities are not to be found everywhere in Greece, there is a clear need for a decentralised approach. Hence, we are proposing to develop a cluster approach which can serve groups of industries in various locations in the country. For sectors such as refineries, the steel industry, the chemical industry and the cement industry, that lack practical decarbonisation alternatives, CCUS hubs in different locations in Greece could serve as an open-access utility. It is worth noting that pipelines, local and cross country, are considered as an important part of the CCUS hubs, since they can assist in the aggregation of captured CO_2 from different emitters located nearby.

The broad concept of the setup and operation of the proposed CCUS hub is depicted in Figure 24. Ports, which are necessary for CO_2 shipping purposes, have a significant role to play as part of the overall CCUS supply chain.

The main parts of the CCUS value chain include CO_2 capture, transport, storage and utilisation, whereas the value chain system further includes the sectors of planning and design, purchase and manufacture, distribution and sale, as well as financing and legislation. In order to assure the required skills, knowledge management guidance, technology and infrastructure needed, as well as opportunities for innovation it is important to understand all these parts and sectors of the CCUS value chain in Greece and make them accordingly operational (63) (64).

CCUS hub components

The basic CCUS hub components are outlined as follows:

- Capture mechanism in each industrial plant
- Liquefication unit in each industrial plant
- Limited local pipeline network
- CO_2 steel storage tanks
- CO_2 loading facility
- CO_2 vessel

Figure 24a and 24b show the broad CCUS hub concept which we are proposing.

Figure 24a: Hub block diagram displaying the overall land-based hub architecture.

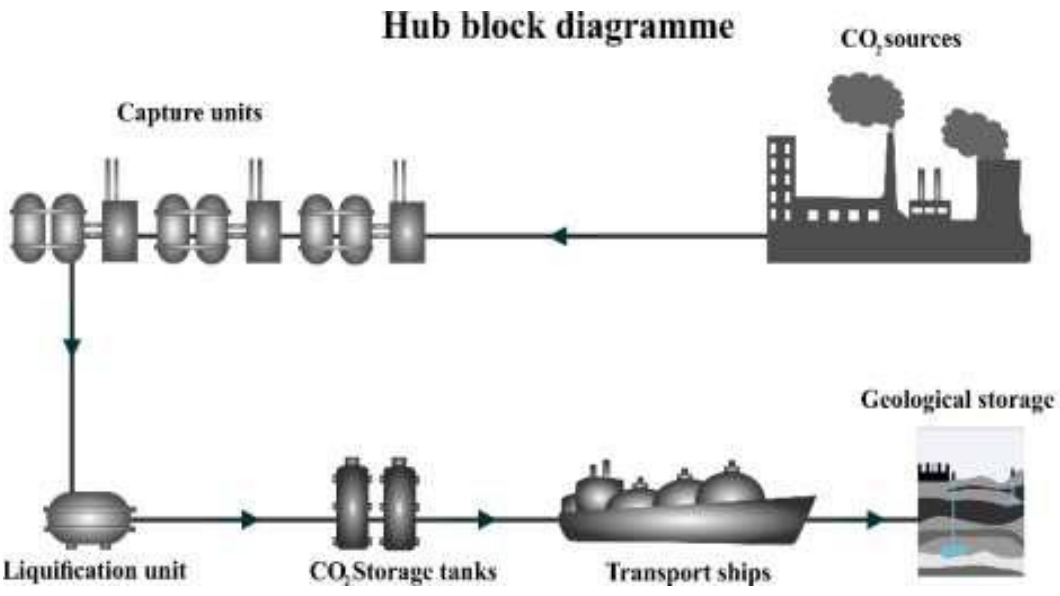
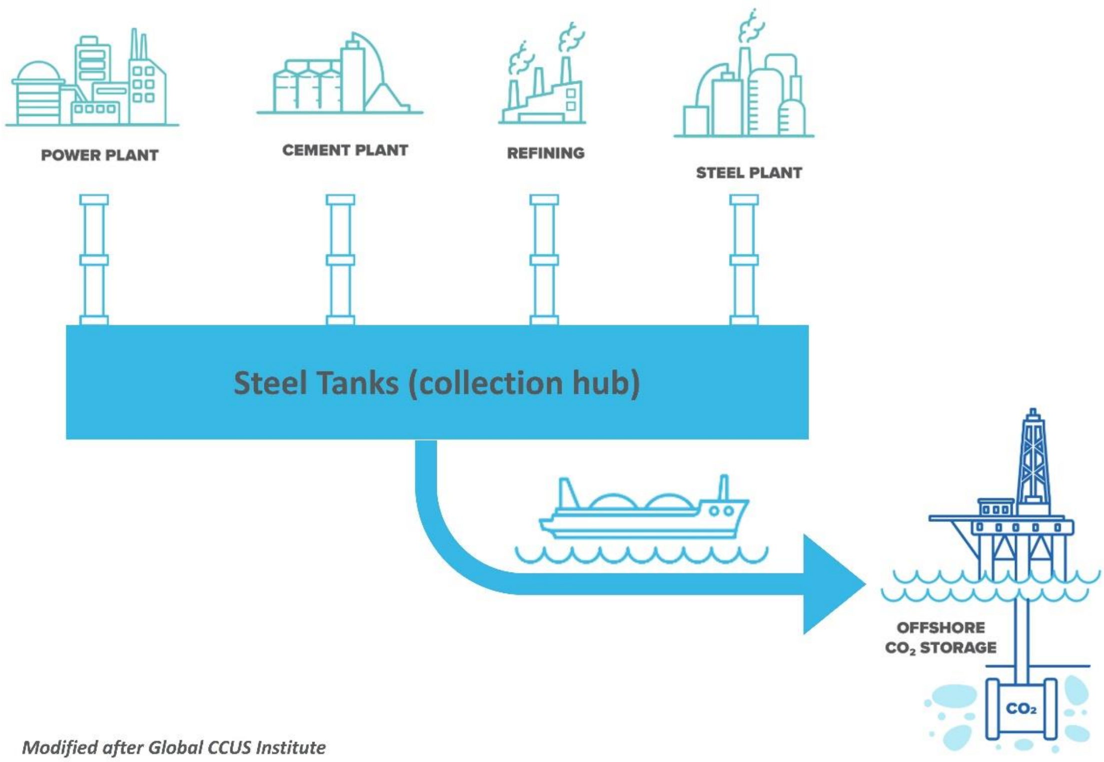


Figure 24b: The envisaged CCUS hub and cluster network



Modified after Global CCUS Institute

The role of ports is essential in the organisation and operation of such hubs. Most ports in Europe, including those in Greece, are situated either at an embayment or on a shoreline that has been artificially created. Others are situated near estuaries and have access to the sea via a canal system. Large ports like Rotterdam, Duisburg, Hamburg, Humberside, Teesside, Grangemouth, Antwerp, Le Havre, and Merseyside already have several of Europe's biggest carbon emitters (both power plants and industrial complexes) "clustered" together (65). The port of Rotterdam is by far the biggest in the EU, close to Antwerp, which is home to the second largest port. The Rotterdam port area accounts for 14% of all CO_2 emissions in the Netherlands (66), hence its contribution to achieving the country's climate goals is crucial. Construction of an onshore pipeline running through the port of Rotterdam, a compressor station, and an offshore pipeline to access gas resources for CO_2 storage are all part of the development of CO_2 transport and storage infrastructure at the Port of Rotterdam (67).

Ports offer space for industrial and commercial activity as well as support for numerous ships and boats (transferring passengers or cargo). Moreover, ports can serve as hubs for the connection of several industries, including neighbouring industrial operations, energy production, inland and maritime transportation. It should be stressed that ports provide the necessary outlet for the seaborne transportation of CO_2.

In the typical case of LNG, a typical current paradigm with regard to ports is the Revithoussa LNG Terminal situated 45km west of Athens on the islet of Revithoussa in the Gulf of Pachi at Megara. The Revithoussa LNG Terminal is one of the twenty-eight LNG terminals that are currently operating in the wider Mediterranean region and in Europe. It is the only LNG terminal in Greece that receives LNG cargoes, temporarily stores and regasifies LNG, and supplies the National Natural Gas Transmission System.

In the region of Alexandroupolis, the second floating natural gas infrastructure that will operate in the country is expected to be completed in 2023, contributing the most to strengthening the energy system (68). The Floating Storage and Regasification Unit (FSRU), with a capacity of 153,500m^3 LNG, will be connected to the National Natural Gas Transmission System of Greece with a 28km-long pipeline (69). The FSRU will be moored at a distance of approximately 18km, in the sea, southwest of the port of Alexandroupolis and 10km from the nearest coast at Makri of Evros.

Potential CCUS hubs in Greece

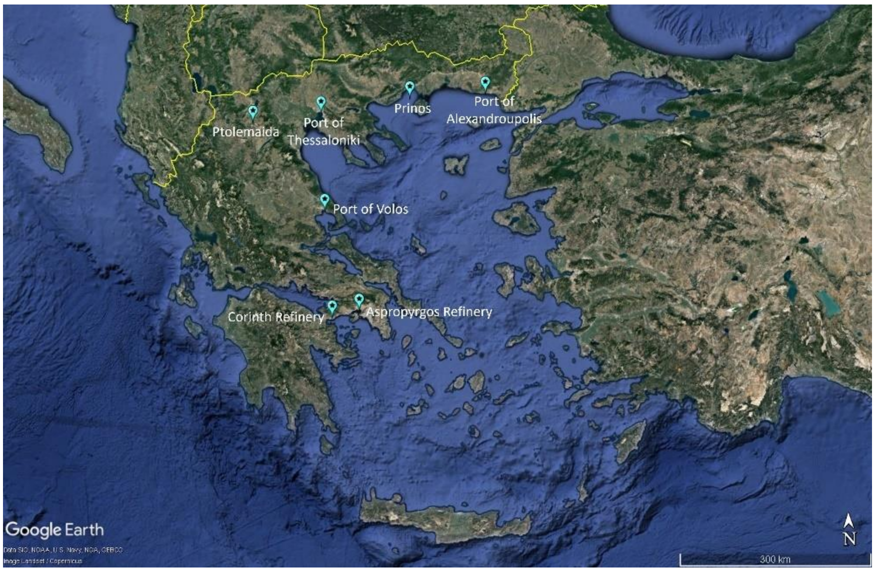
Looking into CCUS hub development prospect in Greece over the next 10–15 years, a number of potential onshore hubs are examined within or near port facilities since the shipment of collected CO_2 for permanent storage is recognised as an essential element in the value chain.

Five (5) potential onshore hubs in addition to the Prinos underground storage facility are being considered (Figure 25):

- Prinos hub
- Thessaloniki hub
- Alexandroupolis hub
- Ptolemaida Western Macedonia hub
- Corinth and Aspropyrgos hub
- Volos hub

Some of the CO_2 volumes captured may end up in the Prinos facility, while others may be shipped further afield within the Mediterranean basin.

Figure 25: Potential hub locations in Greece (Source: Google Earth Pro v.7.3).



Establishing the CCUS value chain

The proposed timeline type of roadmap for the establishment of CCUS hubs in Greece is unfolded in Figure 26. The roadmap has been prepared based on the current available information concerning plans and announcements by various companies and the government's commitment as part of the new NECP.

In order to effectively apply CCUS in Greece, it is important to examine and fully comprehend the CCUS value chain, and to plan a roadmap with the necessary steps/stages to make possible the implementation of relevant projects in Greece.

It is mandatory to map the existing opportunities for CO_2 storage, as well as the required technology, infrastructure, knowledge and expertise gaps within. Therefore, this roadmap aims to present and describe the initial activities that the Greek government and industries need to take on in order to apprehend the world-class potential of the CCUS supply chain, and to maximise the attractiveness of the CCUS application in Greece, from the perspective of investors.

Engagement of key stakeholders and industries

The barriers to deploying CCUS projects in Greece, are both commercial and technical. The latter are linked to the first, since insufficient commercial promotion decreases the popularity of CCUS projects. This has further impact on public awareness and concurrently increases the cost of finance, CCUS technologies and infrastructures. It also creates higher risk for the investors and may prevent stakeholders from funding relevant projects or signing CCUS contracts. To overcome these barriers, it is vital for Greek authorities to develop profitable and stable commercial bases, in order to promote the engagement of stakeholders, and help them make investment decisions with reduced and provisioned risk. Apart from the financial and governing investments that need to be made, it is essential to increase the competitiveness of the Greek CCUS supply chain in relevant European or international projects. Also, developing CCUS projects will help Greek companies to increase their competitiveness and opportunity for finance and growth (63).

Roadmap for CCUS implementation in Greece

A roadmap for CCUS application in Greece outlines a strategic and progressive approach to address carbon emissions and climate change challenges. This roadmap envisions a multi-year journey, beginning with feasibility studies and funding proposals in the initial years. As the roadmap unfolds, it transitions into infrastructure development, operationalizing CCUS facilities in key regions, and expanding the network of hubs across the country. By adhering to this roadmap, Greece can effectively harness CCUS technology to capture, utilise, and store carbon emissions from various industries, marking a significant step towards a more sustainable and environmentally conscious future. This roadmap not only aligns with global efforts to combat climate change but also showcases Greece's commitment to playing a pivotal role in reducing carbon emissions and securing a greener tomorrow (Figure 26).

2024: Setting the Stage

In 2024, the Greek CCUS initiative kicks off with the completion of a comprehensive feasibility study. This study will provide crucial insights into the technical, economic, and environmental aspects of CCUS implementation in Greece. With the feasibility study's findings in hand, the next step is to submit a funding proposal to the European Union (EU), seeking financial support for the ambitious project. Successful completion of these two initial stages is essential to lay the foundation for the Greek CCUS cluster's development.

2025: Securing EU Funding and Engineering Design

Building upon the groundwork established in the previous year, 2025 focuses on securing EU funding for the Greek CCUS cluster. This financial support is instrumental in realising the project's scale and impact. Simultaneously, detailed engineering design work begins for the first CCUS hub. This stage is critical to ensure the effective and safe capture, utilisation, and storage of carbon emissions.

2026: Initial Operations and CO_2 Carrier Vessels

The year 2026 marks a significant milestone as the Prinos CCUS facility commences operations, demonstrating the feasibility and effectiveness of the CCUS technology in the Greek context. Additionally, to facilitate the transportation and storage of captured CO_2, orders are placed for the construction of CO_2 carrier vessels, which are essential for the Greek CCUS cluster's long-term success.

2027: Expanding Horizons

With the Prinos facility running successfully, the focus in 2027 shifts towards expanding the CCUS infrastructure. Construction begins on the first CCUS hubs in Elefsina and Agioi Theodoroi. Simultaneously, feasibility studies are initiated for potential CCUS hubs in Thessaloniki and Alexandroupolis, broadening the scope of the Greek CCUS cluster.

2028: Infrastructure Development

In 2028, the construction of the Elefsina and Agioi Theodoroi CCUS hubs is completed, marking a major step forward in Greece's CCUS journey. CO_2 carrier vessels are also delivered, enhancing the cluster's capability to transport and store carbon emissions. Furthermore, operations commence at these hubs, enabling the capture, utilisation, and safe storage of CO_2.

2029: Expanding Operations and Design

The year 2029 sees the initiation of construction for the Thessaloniki and Alexandroupolis CCUS hubs, further extending the Greek CCUS cluster's reach. Meanwhile, the design phase for the Volos CCUS hub begins, ensuring a comprehensive and systematic approach to expanding the infrastructure.

2030: Full-Scale Operations

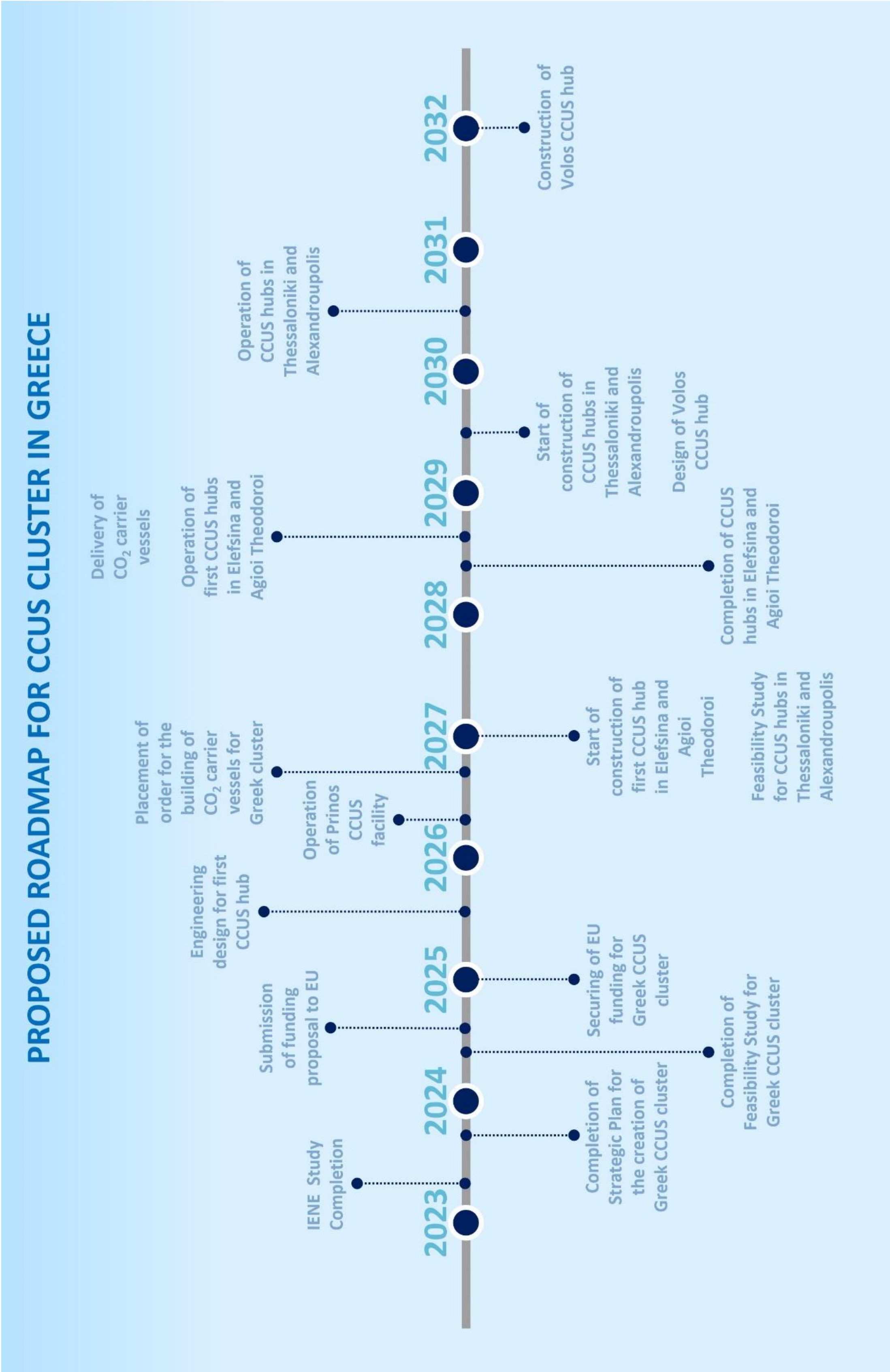
By 2030, the CCUS hubs in Thessaloniki and Alexandroupolis become operational, effectively covering multiple key regions in Greece. This marks a significant achievement in Greece's commitment to reducing carbon emissions and combating climate change.

2032: Completing the Vision

In 2032, the construction of the Volos CCUS hub is completed, finalising the Greek CCUS cluster's infrastructure. This comprehensive network of hubs spans the country, effectively capturing, utilising, and safely storing carbon emissions from various industries and sectors.

The roadmap outlined above provides a clear and systematic approach to the development of CCUS cluster in Greece. From initial feasibility studies to securing EU funding, from constructing the first hubs to expanding operations across the country, Greece's CCUS initiative demonstrates its commitment to sustainability and addressing climate change. By following this roadmap, Greece can play a pivotal role in mitigating carbon emissions and contributing to a more sustainable future for all.

Figure 26: Proposed roadmap for CCUS applications in Greece.



Chapter 6: Legal and regulatory issues

It is important to note that the damages arising from potential occurrences of CO_2 leakage can be either local or global, considering that on the local level, such a leakage near the storage site could harm indirectly people and livestock.

However, if there is ground water contamination or leakage to the atmosphere it is not possible to measure the impacts as restricted within the territory of one state. Especially when it comes to leakages in the atmosphere, further burdening the phenomenon of global warming, the responsibility of prevention or the liability once it happens is crucial, universally. (70).

Having taken these into consideration, the moral and more importantly the legal challenges of the development and implementation of CCUS technologies and methods are quite complex and they lie upon – not only the issue of liability and environmental protection – but also on the broader framework necessary to govern how these can be studied and licensed in ways that minimize the aforementioned risks. On top of that, similarly to every other modern technology, the framework on how investing on it will be incentivised is important too.

In order to have a complete regulatory framework on the use of CCUS in Greece, it is necessary to examine other such frameworks that have been established already. CCUS projects have been developed and operating in several areas across the globe, such as the USA, China, Canada, Australia and Norway.

Among these, Norway is an example of implementation of the Directive 2009/31/EC on the geological storage of carbon dioxide, for the EEA (European Economic Area), while other useful European regulatory tools for this framework are the Environmental Liability Directive (Directive 2004/35/EC of 21 April 2004 on environmental liability with regard to the prevention and remedying of environmental damage [2004] OJ L143/56 (ELD) and the Emission Trading Scheme Directive (Directive 2003/87/EC of 13 October 2003 on establishing a scheme for greenhouse gas emission allowance trading within the Community [2003] OJ L275/32, as amended by Directive 2009/29/EC [2009] OJ L140/63).

In Norway, CCUS falls with the authority of two different ministries based on whether it is considered as petroleum activity or not, and these are the Ministry of Petroleum and Energy and the Climate and Environment Ministry, regarding broader environmental issues of its use. In general, the country's framework on CCUS includes the necessity of risk assessment for a project as part of its permit application stage, while it is also foreseen that an operator of the storage site must prove that all the obligations regarding the storage permit can be financially met. (71).

In addition, according to the Norwegian Ministry of Petroleum and Energy and the country's Petroleum Act, the licensing process of a project includes the following.

- Prospecting license
- Exploration license
- Exploitation license
- Post-closure: Transfer of responsibility to State / Ministry of Petroleum and Energy
- Financial mechanism

Additional issues that need to be considered are environmental issues, the storage license and the issue of the financial security of the activities. (72).

Greek regulatory framework

Greece as part of the European Union cannot fall far from what the EU Directive suggests being the base on a regulatory framework on Carbon Capture and Storage. However, as preparing the national framework on CCUS there are some particular issues that need to be taken under consideration.

To begin with, it is important for the national legislator to decide whether the CCUS activities should be – at least partially - considered as petroleum activities, on the sense that such activities are mostly useful to decarbonise the energy production based on fossil fuels; or not, considering that CCUS activities can also apply on heavy industries the workflow of which includes high CO_2 emissions. Either way, the ministry under the authority of which, CCUS would fall, in Greece, is the Hellenic Ministry of Environment and Energy, while the main connection with the legislation on petroleum would be regarding the exploitation of specific sites and the way it can be governed.

In addition, it is also important for the legislator to determine if CO_2 can be classified as waste or hazardous waste or if it should be addressed as a commodity. Across the global practice, several reports and proponents of CCUS have noted that it should be treated as a commodity and not as a pollutant or as waste. Regarding this, it is important to note that internationally, atmospheric CO_2 is not considered a waste according to the Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and Their Disposal, 1989. However, the environmental risks arising from its inadequate management should not be ignored. (73).

In fact, whether CO_2 shall be treated as a commodity or as a waste is of utmost importance considering that the legal nature of the CO_2 captured and stored highly affects issues related to the liability of the stakeholders involved. In particular, if CO_2 captured is considered a waste there is only the issue of liability to be addressed regarding potential consequences on the environment. On the other hand, if it is considered a commodity, it means that someone of the stakeholders involved shall have ownership rights on it, as well as right to utilise it at will. In that case, there should also be defined which of the stakeholders involved should have such ownership rights between the CO_2 producer and the storage operator, as well as how their interaction should be framed. On top of these, if CO_2 is treated as a commodity, challenging regulatory issues of incompatibility with the EU ETS will have to be addressed too.

Furthermore, considering what has already been presented and the fact that boosting investments on CCUS will need to be adequately incentivised in the country, the legislator will have to frame how the CO_2 captured can be excluded from the obligation to pay quotas within the EU ETS. A provision that will encourage not only the companies in the energy sector to engage in CCUS but also the heavy industries and the Energy Intensive Industries that will either use CCUS in order to mitigate their own CO_2 emission or will be supplied with electricity produced by fossil-burning electricity generation units where CCUS is being used. This way, the Energy Intensive Industries will have the option to consume electricity from producers that have already reduced their CO_2 emission form the electricity generation process even if their production is based on fossil fuels. On the other hand, these industries that have long workflow processes that include stages of burning material and emitting CO_2 on site, CCUS should be foreseen as an alternative for them to minimize their CO_2 emissions and to lower their quotas expenses respectively as well.

The regulatory framework on the development of CCUS projects in Greece shall include, namely, the following parts:

1. Scope
2. Terms and Definitions
3. Independent Authority on CCUS
4. The licensing procedures

   A. CO_2 capture permits
      - Environmental permit
      - Environmental Impact Assessment
      - Eligibility criteria
   - Application process and content
   - Permit issuance
   - Permit content
   - Permit duration, withdrawal, modification, transfer or renewal

   B. CO_2 transport permits
      - Environmental permit
      - Environmental Impact Assessment
      - Eligibility criteria
   - Application process and content
   - Permit issuance
   - Permit content
   - Permit duration, withdrawal, modification, transfer or renewal

C. CO_2 storage permits

1. Prospecting license
   - Environmental permit
   - Environmental Impact Assessment
   - Eligibility criteria
- Application process and content
- Permit issuance
- Permit content
- Permit duration, withdrawal, modification, transfer or renewal

2. Exploration license
   - Environmental permit
   - Environmental Impact Assessment
   - Eligibility criteria
- Application process and content
- Permit issuance
- Permit content
- Permit duration, withdrawal, modification, transfer or renewal

3. Exploitation license (CO_2 storage permit)
   - Environmental permit
   - Environmental Impact Assessment
   - Eligibility criteria
- Application process and content
- Permit issuance
- Permit content
- Permit duration, withdrawal, modification, transfer or renewal

D. Health and safety permits

5. CO_2 storage sites selection

6. Third party access

7. Closure and post-closure

8. Financial mechanism

9. Monitoring

A. CO_2 capture

B. CO_2 transport

C. CO_2 storage

10. Reporting

A. Registers

B. Internal reporting

C. External reporting

11. Liability

12. Dispute resolution

13. Public participation

14. Enforcement

Policies

Currently, there are several European legislations and policies that are able to support and promote CCUS applications at a European and, concurrently, national level. As described in the European CCUS Roadmap to 2030, these are the Trans-European Networks for Energy (TEN-E) regulation, the EU Emissions Trading System (ETS) regulation, the Hydrogen and Gas market decarbonisation package, the Industrial transition pathways, the CEEAG State Aid Guidelines, the EU Taxonomy for Sustainable Finance, the Important Projects of Common European Interest (IPCEI), and the Renewable Energy Directive (63). Similar regulations should be developed by the Greek government, in order to endorse sustainable solutions to decarbonisation, including CCUS applications.

The emphasis given to the necessary governmental changes that are mandatory to enable CCUS applications is attributed to their direct impact on the development of related technologies and infrastructures. Apart from funding support and promoting CCUS at a national level, the prices of technology and infrastructure needs to be reduced to make them attractive from a political and investing perspective (63). The general shift to renewable energies and decarbonisation solutions of the European Union, the gradually increasing number of CCUS applications in other European countries, as well as the creation of CCUS hubs throughout Europe (namely Porthos, Athos, Antwerp CO_2, Acorn Sapling, and Ervia), gives a positive and promising motion towards CCUS projects. This may further encourage Greek government to set helping regulations and policies, viewing CCUS as a promising future solution for achieving both carbonization and economic growth at a national level.

Conclusions and Key Messages

- CCUS is a pioneering technology that can contribute on a large scale not only to decarbonisation, but also to circular economy, via the re-use of the captured carbon dioxide and the re-storage after the utilisation, for a repeating and complete circle.
- The technology and know-how exists today in Europe and worldwide which will enable the introduction of CCUS in Greece over the next few years.
- The time span envisaged for CCUS applications in Greece is 10 years as exemplified in the roadmap which has been charted out in the context of the present study.
- There are several locations in Greece that could serve as potential CO_2 collection and storage sites, either via in-situ injection and CO_2 storage within deep saline aquifers, hydrocarbon reservoirs, and porous sandstone reservoir formations, or by the permanent CO_2 sequestration via mineralization in specific rock formations.
- The depth of the unmineable lignite sites in Ptolemais and Kozani are quite shallow and need to be considered regarding the supercritical conditions of CO_2 storage at depth. However, the Mesohellenic Trough presents several advantages, so do the larger areas east and west of Thessaloniki.
- In addition to underground CO_2 storage there is a need for on land storage facilities which will form an integral part of a total CCUS hub.
- In order to effectively apply CCUS in Greece, it is important to examine and fully comprehend the CCUS value chain, and to plan a roadmap with the necessary steps/stages to make possible the implementation of relevant projects in Greece. It is mandatory to map the existing opportunities for CO_2 storage, as well as the required technology, infrastructure, knowledge and expertise gaps within.
- In Greece, several companies operating in the most polluting industries are now including CCUS in their energy transition plans, a trend that is expected to be accelerated by the ever-increasing costs of CO_2 emissions and the wider availability of CCUS technologies.

- Further research is needed as there is still lack of data for the implementation of CO_2 storage projects in most of the proposed candidate locations. Apart from the storage capacity of the reservoirs, long-term storage stimulations and risk assessments are mandatory, in order to ensure the safety and the efficiency of the operation. Detailed financial assessment for all locations is needed in order to drive conclusions about their profitability.
- There exists a critical mass of emissions in Greece today, from industry and power generation, which is capable of supporting a cluster of decentralised CCUS hubs.
- The proposed country wide cluster can include the Prinos underground facility along with a number of other, overland, CCUS hubs.
- Given their specialised nature and the long time needed for their building, the availability of CO_2 vessels emerges as a critical component in the CCUS value chain.
- In view of the high level of emissions involved in the East Med basin, it is reasonable to pursue a development path involving both underground and overland CCUS hubs.
- The management of emissions from PPC's lignite power stations in the Kozani/Ptolemais area has been left out of the present study, in terms of the pursued roadmap, as the Corporation's management is not willing to discuss any based on CCUS technologies.
- Following the present study, it is important for more research to be carried out in order to determine in detail the precise amount of emissions involved in the broader region and how the Greek based CCUS cluster can cater for them.
- Carrying out a detailed cost benefit analysis is absolutely necessary in order to understand the economics of the proposed CCUS hub concept and under what conditions it can be applied in Greece.
- The next step in our investigation of the application of CCUS in Greece will be, with the help of mathematical modelling, to try and visualise how a CCUS nationwide market will work.
- Equally important is to be able to identify the technical and non-technical obstacles and barriers involved in the whole process of introducing CCUS technology and the associated market operation in Greece.

- In order to be in a position to describe the operation of a future CCUS supported emissions market in Greece, one must take into consideration a regulatory framework which, alas, is absent today. In this respect, the present study has looked into this matter and is proposing a suitable framework in line with European and international experience.
- The lack of an adequate regulatory framework for emissions management and CCUS applications in Greece should not act as a disincentive in our effort to introduce CCUS and invest in this area of enterprise.
- There are synergies involved between carbon capture and storage energy production, such as utilization of geothermal energy or blue hydrogen. This could prove to be a great advantage in our efforts to combat climate change and increase the energy efficiency and competitiveness of the country.

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From 1997 to 2012, as president of Georex group, when he demerged the exploration assets from the service activities and established technical subsidiaries in France, United Kingdom, Tunisia and the Republic of Congo. Managed database projects on CIS reservoirs, data mergers for Total, PetroFina and Elf, seismic data transcription for Snpc and Esso. Between 1996 and 2000 he directed evaluation teams for the development of oil and gas interests in Texas and Colombia. Before joining the petroleum industry, Mr. Bassias had an academic career at the Free University of Berlin and was also Associate Professor in the National Museum of Natural History in Paris.

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Dr Koukouzas holds a PhD in Industrial Mineralogy from the UK and has over 27 years of experience in industrial geology, energy technologies, geomechanics, applied petrology and CO_2 geological storage. Since 2003, he is the Director of Research at the Centre for Research & Technology Hellas / Chemical Process and Energy Resources Institute (CERTH/CPERI) and Scientific Responsible at over 55 EU research projects, with a team of more than 40 scientists. Previously, he held positions as Policy Officer, Detached National Expert in the European Commission, Direction General for Energy (DG ENER) (2020-2022), Coordinator of EU experts and Gulf countries experts on Carbon Capture and Storage for the EU-Gulf Countries Clean Energy Network (2010-2013) and, Scientific Officer, Detached National Expert in the European Commission, Direction General for Energy and Transport (1999-2003). Furthermore, Dr Koukouzas has served as a member of the Board of Directors of the Greek Institute for Geology and Mineral Exploration (IGME) and a Consultant to energy, construction and cement industries.

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Mr. Costis Stambolis who is the Executive Director of IENE, has a background in Physics and Architecture having studied at the University of London, the North East London Polytechnic (NELP) and the Architectural Association in London from where he holds a Graduate Diploma in Architecture and Energy Studies (AA Dip. Grad). He also holds a professional practice license from the Technical Chamber of Greece (TEE), and a Masters Degree from the Said Business School, University of Oxford, where he studied "Strategy and Innovation".

Costis has carried out numerous studies and projects on Renewable Energy Sources in developing countries. He has consulted widely on solar building applications for both private and institutional clients in various European countries. He has worked as a consultant and strategy advisor on natural gas, oil markets and energy security issues for large multinational companies, international organizations and governments.

Costis has lectured widely on energy issues and has organised several national, regional and international conferences, seminars and workshops. He has published several books, conference proceedings, research papers and studies on energy policy, solar energy, RES and energy markets. Among pthers he is the editor of the "S.E. Europe Energy Outlook (2011,2017, 2022)", which considered a basic reference on energy for SE Europe.

Since 2001 he supervises and edits daily Greece's foremost energy sitewww.energia.gr. He is a founding member of the Institute of Energy for South East Europe (IENE), which he currently chairs. He is a member of the Energy Institute (UK), the International Passive House Association (IPHA), The Technical Chamber of Greece (TEE). Since 2018 he also serves as a full member of the Greek government's standing committee on Energy and Climate Change (NECP).

- ## Study Advisor

Ms. Evgenia Koroneou, Strategic Energy and Policy Advisor

Evgenia Koroneou has over 30 years of experience in the Energy, Sustainable Innovation and Life Sciences industries, exercising her senior executive roles in Global 500 companies (1990-2016) and working as Growth and Change Consultant & Strategic Energy and Policy Advisor (2016-today). She has a cross-industry and cross-functional proven record in developing new business, in negotiating, deal closing & managing large-scale complex projects in diverse markets incl. Europe, MEA, LAM, and NAM, in driving global mindset change & transformation initiatives as well as in coaching & mentoring people worldwide.

As Head of Power in Alstom, Greece-Cyprus (2008-2014), she developed and managed the Alstom offer for the 1st CCS-ready Ptolemais V power plant (1.25 billion Euros) and cooperated closely with IENE, Public Power Corporation, Mytilineos Group and Energean in the early introduction of CCS technologies in Greece.

As Consultant and Advisor, she supports with her expertise companies and institutions to recognise the challenges they are facing and helps them to resolve their operational issues to achieve sustainable growth by translating ambitious visions into profit, revenue, new role models, methodologies, and tools.

Living in Zürich since 2002, Evgenia is also a pro bono mentor in the ETH University (Master of Advanced Studies in Management, Technology and Economics, MAS-

MTEC) and Thrive with Mentoring organisation, the latter supporting women's empowerment. She holds a M.Sc. in Electrical & Mechanical Engineering, a post-grad diploma in Energy & Environmental Management and academic credentials in strategy, leadership in turbulent times, complex decision & deal making from University of Saint Gallen and IMD Business School.

ISBN: 978-960-99940-6-4

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